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A PRELIMINARY ASSESSMENT OF WET SYSTEMS FOR RESIDENTIAL REFUSE COLLECTION

Curran Associates, Incorporated

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16. ABSTRACT

The most promising wet system alternative is identified as a system using individual household grinders in low density areas, vacuum collection and neighborhood grinders in high density areas, dilute slurry transport of ground refuse in the existing sanitary sewer systems, and joint treatment of refuse and sewage at an expanded treatment facility that includes anaerobic digestion for methane generation. However, the economic feasibility of even the most promising alternative is doubtful because of the high cost of grinding, and hydraulic transport of ground refuse in existing sewer systems may be feasible only if both metals and glass are excluded. A conventional collection of the nongrindable and bulky constituents of residential refuse will still be needed, albeit of a diminished frequency. The total 1973 cost of such a wet system is estimated at $113-$196 per household per year of which $80-$105 is for grinding. This compares to a total cost for refuse and sewage collection and disposal under existing concepts of $43-$115 per household per year. Projections for 1988 indicate that the wet system cost might rise to $130-$228, against a range of $61-$143 under conventional concepts. However, if the cost of the grinder is excluded (on the basis that individuals would purchase grinders for their convenience benefits), the 1973 wet system costs (to the public sector) would be only $33-$91 (as against existing public sector costs of $43-$115).

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

As part of these activities, the study described here presents an investigation to determine the feasibility of hydraulic transport of ground refuse in sanitary sewers of conventional design.

This report is one of several final reports examining the technical and economic feasibility of collecting and transporting residential solid wastes via an underground, wet pipeline (sewer) system. The research was aimed at improving the overall management and reuse of solid waste to the benefit of both the individual citizen and the national environmental picture. All possible aspects of this new concept were considered including the physical, mechanical, chemical, and socio-economic, and the environmental. It is the conclusion of the study that the wet system concept is extremely feasible technically, socially, and environmentally; but that the system's economics do not appear too reasonable at this time except for specialized applications.

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SUMMARY OF CONCLUSIONS

The economic feasibility of a system utilizing domestic grinders, transport of the refuse slurry in an existing sewer system, and joint treatment of sewage and ground refuse is dependent on the cost of grinding. The total annual cost per household for such a system is estimated at \$113-\$196, of which \$80-\$105 is for grinding. This compares with an estimated total annual cost for refuse and sewage collection and disposal under existing practice of \$43-\$115 per household.

Briquette flow in gravity sewers, and pressurized alternatives of slurry systems, are not considered feasible for refuse collection. Alternatives using vacuum collection to neighborhood grinders are only feasible under high residential densities.

The technical feasibility of transporting ground refuse in gravity sewers is definitely established only if both metals and glass are excluded. It is doubtful whether the scour velocities necessary to flush out deposited glass solids are present in the lateral sewers of minimum slope and low flows typical of residential areas. Ferrous metals need to be excluded also because grinding power requirements are in excess of those that could easily be provided in the individual home.

The major uncertainty in the treatment of ground refuse at sewage treatment plants is the possibility of hazardous, nonbiodegradable materials in the refuse being unaffected by existing treatment processes and therefore entering the environment by a more rapid route than by way of landfill leachates. The extent of this problem is unknown because of insufficient information on the presence of such materials in residential refuse.

The major impact of the addition of ground refuse at the treatment plant will be in preliminary, primary and sludge handling operations. Subject to the previous conclusion, the impact on secondary and advanced waste treatment is likely to be marginal as the additional load on these processes appears to be no greater than the load variations at existing sewage treatment plants, especially those treating ground garbage.

The per ton cost of sludge handling at a treatment plant handling both sewage and ground refuse will be much lower than the cost of existing treatment plants. Economies of scale, improved dewatering characteristics and the ability to obtain high solids concentrations by judicious choice of preliminary and primary treatment processes are the major reasons for this. Thus, the costs of sludge handling at a 10 mgd plant might fall from \$50/ton to \$23/ton if ground refuse were present.

The best opportunity for resource recycling under a wet system lies in conversion to energy rather than materials recovery. The possibility of methane generation from anaerobic digestion is attractive from an economic standpoint because of the serious shortage of natural gas and therefore favorable market conditions for its major constituent.

CHAPTER I

INTRODUCTION

The Concept of Wet Systems for Residential Refuse Collection

The wet system for residential refuse collection of prime interest to this research involves the use of the existing sewer system to transport domestic refuse from the individual home to the point of treatment and disposal, thereby eliminating conventional house-to-house collection by trucks. This idea depends on three technical prerequisites: the feasibility of reducing refuse in the home to a size suitable for hydraulic transport, the feasibility of transport of ground refuse in an existing sewer system without deleterious effects, and the feasibility of joint treatment of refuse and sewage at an existing or modified treatment plant. Implementation of the idea requires also economic feasibility, which demands that a rigorous cost-benefit analysis shows the proposed system to be economically favorable over other existing and proposed systems.

From the viewpoint of solid waste management, the major incentive for analyzing such a concept is the high cost of collection. The increasing costs are due primarily to an increase in per capita waste generation and an increase in labor wage rates. As noted by Clark,[1] the latter has been far in excess of inflationary trends as the increasing tendency for collective bargaining has had a substantial effect on the wage rates for individuals employed in local solid waste management functions. Although productivity of collection in the last decade has increased substantially, there are limits to further increases under the constraints of existing solid waste management concepts; substitutions of capital for labor can be accomplished only to the point of having a one-man crew on a truck so large it can no longer efficiently navigate the streets and, consequently, only basic changes to existing practice offer any hopes to reduce the cost of solid waste collection.[2]

There are several alternative variations to the basic idea that also merit serious investigation. Because of the significant economies of scale in size reduction devices such as grinders, the alternative of installing these on a neighborhood rather than an individual home basis must also be examined. This in turn would require some means of refuse transport from the individual home to the grinder location. Pneumatic pipeline systems seem particularly suited to this latter task. Some form of sewer pressurization may also be advantageous where the existing sewer system cannot handle the increased solids loads to be expected from the addition of ground refuse.

In one respect, the concept is a natural step in this historical evolution of man's arrangements for removal of wastes from his place of living. The open street channels of medieval times, operative only during the rain, were put underground and adapted for continuous disposal of sewage.[3] Since the start of this century, the sewerage system in turn has been used for a continuous removal of putrescible garbage through the introduction of under-sink kitchen garbage grinders. The use of sewers for the continuous removal of refuse is thus a logical further step in this evolution. It can be argued that just as it became unacceptable in the last century to store human excrement until times of rain, or unacceptable in this century to store garbage in the open and accessible to vectors until the time of manual collection, so will the storage of the remaining domestic wastes be unacceptable in the future. Even if sewers are rejected in favor of vacuum or pressurized hydraulic systems for this purpose, continuous removal of domestic refuse is but a matter of time.

On the other hand, much recent thinking has emphasized the need to reduce, rather than increase, the burden on the sewer system and its treatment facilities. Consequently, the idea of drastically increasing the burden on existing treatment plants is objectionable to many, understandable in view of the deficiencies in existing technology and operation of sewage treatment plants. Yet, the existing practices of solid waste collection are equally objectionable to other observers; noisy, dirty, potentially hazardous to public health, inconvenient, inefficient and costly. Indeed, the deficiencies in almost all aspects of environmental quality management and the interdependence of air, water and land, stress the importance of considering the problem of environmental quality as a single entity. The philosophy embodied in this report is, therefore, a joint, rather than separate, examination of the problem of solid waste management and sewage collection and treatment.

Technical Feasibility

However attractive the concept of wet systems for residential refuse collection may appear from environmental and socioeconomic viewpoints, viewpoints elaborated on in following sections of this chapter, the technical feasibility of the concept has yet to be convincingly demonstrated. Although experiments on a laboratory scale, under controlled steady state conditions, are on the whole encouraging, the difficulties and danger of extrapolations to real conditions still occasion major uncertainties. As this report will show in later chapters, there remain two major areas of technical uncertainty.

Firstly, there is the uncertainty that surrounds the choice of treatment processes or process modification at sewage treatment facilities that will be required to prevent undesirable environmental impacts. This uncertainty is occasioned by the lack of knowledge about specific potentially hazardous materials such as mercury or chlorinated hydrocarbons in domestic refuse. Without this knowledge, it is obviously difficult to select or design treatment processes that would ensure the removal of such materials.

Secondly, there is the uncertainty that still surrounds the hydraulic transport of ground refuse. Experiments on a laboratory scale, under controlled flow and velocity conditions in simulated sewer systems and their appurtenances, indicate that no insurmountable difficulties would occur.[4] But there is no knowledge of the impact in the real sewer systems that are encountered in practice, especially in the laterals where the flows reach design velocities only occasionally.

Basic Limitations of the Wet Systems Concept

Regardless of the technical feasibility of the concept, there are several fundamental limitations to any wet systems concept utilizing the existing sewerage system. The two most important limitations concern the incompatibility of the concept with the presence of combined sewers in many of the urban areas where the concept is most attractive from purely a solid waste management viewpoint, and the incompatibility of the concept with individual home or on-lot sewage disposal systems.

The Problem of Combined Sewers. Many of the nation's cities with the most urgent problems of solid waste management are also characterized by the presence of combined sewers. It is obvious that under existing practices of combined sewer management, the addition of ground refuse would be quite unacceptable. Even at times when no overfows are discharged, the flow and velocity variations in combined sewers would present substantial design problems. However, there are clear indications that combined sewer overflows will require treatment sometime in the near future, and consequently, a more appropriate question concerns the impact of the proposed system on the treatment of combined sewer overflows or on methods to achieve sewer separation. If separation of combined sewers is necessary anyway, then obviously modifications for transporting ground refuse might be accomplished at the same time at a relatively small additional cost. Indeed, if it is shown that major modificatons to an existing sanitary sewer system are necessary for the feasibility of the proposed concept, it may be that cities having combined sewers will be in the best position to implement wet refuse collection, as the reconstruction required to separate the combined sewer system could be justified economically on both benefits to water quality improvement and to solid waste management.

Nevertheless, the presence of combined sewers in many of our cities unquestionably constitutes a serious barrier to implementation of the concept, a barrier that must be carefully examined in this study.

The Problem of On-Lot Systems. The wet system concept, being dependent on sewer transport of refuse, is obviously incompatible with on-lot systems. One answer would be to extend the sewer system to areas served by on-lot systems, but the cost of such an extension to developments of low residential densities that characterize the suburban areas where on-lot systems are most frequently encountered would doubtless be very high. The relationships between residence density and the trade-offs between on-lot and municipal sewer systems have been investigated extensively by Downing,[5] and it is clear that the wet systems concept would drastically shift the existing trade-offs. It is probable that continued conventional collection of areas served by on-lot systems will prove cheaper than extending the sewer system; however, this is a problem that can only be answered in the context of a specific case study.

Economic Feasibility

The uncertainties still surrounding the technical feasibility of the wet systems concept compound the difficulties of a rational economic analysis. But even ignoring these uncertainties, the cost analyses are not promising. If one considers only the engineered system costs, that is, without inclusion of intangible socioeconomic and environmental costs and benefits, the most optimistic prediction for a wet system suggests a total cost for refuse and sewage collection, treatment and disposal that is significantly higher than conventional practice. The biggest single cost item of the wet system is the initial cost of the grinder, which, as we shall see in Chapter VI, may constitute 66 percent of the total annual per household cost of the total wet system cost.

The range of total system costs, as determined in Chapter VI for existing conditions of residential refuse and sewage generation, is $43-115 per household per year for conventional practice as against $113-$196 for a wet system implementation. However, without the grinder, the wet system costs reduce to a range of $33-$91 per household per year. Economic feasibility, therefore, depends largely on perspective; if householders would be willing to pay $80-$100 per year for the convenience of refuse grinders, and only the costs to the public sector were considered, then the wet systems concept might have economic merit. This assumption, however, is not likely to be met in practice. There are simplifications, of course, and we shall seek more detailed answers in the course of this report. But before outlining the more promising environmental and socioeconomic potential of the concept, the reader should bear in mind that the tangible economic feasibility, and hence the ultimate potential for implementation, is at best somewhat doubtful.

Environmental Implications

A transition from existing methods of refuse collection and disposal to wet systems collection and joint treatment with sewage has implications for all sectors of environmental planning and management. Potential impacts on sectors other than solid waste management must, therefore, be carefully considered in an overall evaluation.

By combining liquid and solid waste treatment one might expect cost savings from scale economies and from enhanced operational efficiency. If this were indeed so, then it would follow that if total treatment expenditures were held constant, then better quality effluents might result from merging solid and liquid waste treatment. This reasoning suggests that one reason for implementation of the proposed system would be the improvements in environmental quality that would result. Consequently, the objective of the treatment system must be carefully specified - are we minimizing treatment costs given a particular level of effluent quality or are we maximizing effluent quality given a particular level of expenditure? It is by no means certain that the optimal wet system design will be the same in both cases.

This argument is complicated further if one considers the overall maximization of environmental quality as the goal, rather than merely water quality, or air quality. Because of the trade-offs between air and water quality, might one not consider the possibility of accepting a slight worsening of water quality if total environmental quality were improved by a substantial increase in air quality? This argument is not academic because treatment of refuse at a sewage treatment plant under existing (or even improved) effluent standards may be substantially more expensive than separate treatment. This increase in cost should, therefore, be evaluated in the context of overall environmental quality, and might indeed be justified on the basis of eliminating the air and land pollution problems of existing solid waste management concepts. However, one must at the same time be alert to the introduction of new environmental problems caused by new pathways for potentially hazardous materials.

Impact on Conventional Solid Wastes Management. Although the intent of the wet systems for residential refuse collection is to eliminate conventional collection methods,[6] it is readily apparent that some residual conventional collection will still be necessary, albeit of a drastically reduced scope. Even if grinders were to be capable of handling metals, large bulky items would still need removal. Moreover, many other small constituents in residential refuse are not amenable to grinding in the small grinders of single homes, especially resilient plastics, rubber, leather and some synthetic textiles.

But the conventional collection and subsequent disposal of only the nongrindable constituents will bring some major changes to existing solid waste management practice. Volume will be markedly reduced, and density markedly increased as the light, bulky constituents (paper, food packaging, garbage) are easily ground. The frequency of collection may be very low but acceptable because all putrescible materials will be ground. The increased density and weight of standard containers would require trucks to be fitted with hydraulic lifts for the much heavier full containers, and may demand that all containers be picked up from a rear-house rather than curbside location. Calculations developed in Chapter VI of this report suggest that the density of nongrindables may be up to 100 percent higher than the density of uncompacted raw refuse. (See Table 12.) Changes in truck design to allow for the more difficult compaction of the collected material and the increased axle load would also be necessary; indeed the compactor trucks widely used today may be quite inappropriate under the proposed system. The effect of such modifications on collection costs is discussed in detail in Chapter VI.

Disposal methods would also be affected significantly. Because most of the nongrindable materials are incombustible, incineration of nongrindables is no longer feasible. On the other hand, recovery of metals from the nongrindables will doubtless be aided in the absence of all light, putrescible and bulky components. But note that because of significant scale economies a 90 percent reduction of refuse to be disposed of by conventional means does not imply a 90 percent reduction of disposal cost. Thus, the economies of scale in existing refuse disposal methods are a disadvantage rather than an advantage to our proposed system.[7] Another problem arises for the many cities in the northern parts of the nation that rely on sanitation workers for snow removal, a circumstance that may greatly affect the cost comparisons.

It has been argued that the cost of existing solid waste collection could be substantially reduced were the bulk of domestic refuse reduced by the elimination of glass containers by banning "no-return" bottles. But this idea would also benefit the proposed system, as ground glass is one of the major refuse categories that can be expected to cause problems in sewer transport.

Impact on Water Quality Management. Evaluation of the potential impact on water quality is a complex issue, and requires considerations of how existing solid waste management practices affect water quality as well as how the proposed system would affect water quality. For example, concern has been expressed that many new and potentially hazardous compounds might be introduced into the environment by the proposed system. Yet this concern must be placed in the context of considering the quantity of such substances that already enter the environment; the quantity of possibly toxic compounds in dry cleaners, deodorants, hairsprays and the like that would enter the sewage treatment plant under the proposed system by virtue of remnants attached to their containers is far exceeded by the bulk of the contents of each can which is sprayed on the human body or applied to clothing and which is in turn washed off in bathtubs, showers and laundries. Other toxic metals and exotic compounds mentioned as possibly dangerous, such as mercury from mercury batteries or paint remnants from empty paint cans, are of concern also under existing solid waste management practices, entering the environment by way of landfill leachates, although it should be pointed out that in most cases leachates do not enter water supplies by as direct a route as do treatment plant effluents.

Nevertheless, it is clear that the effectiveness of the treatment facility will ultimately govern the impact on water quality, and consequently the objective of the facility must be carefully specified, as noted previously. Because the future will bring considerable modification to existing treatment practice as advanced waste treatment processes come to be needed to meet the very stringent anticipated effluent quality standards, an assessment of the impact on water quality must, therefore, concern itself with the impact on the effectiveness of treatment plants of the future, as well as treatment plants of the present.

Impact on Air Quality Management. Implementation of the proposed system in urban areas would undoubtedly have a significant impact on air quality.[8] Although many cities now prohibit in new buildings the on-site refuse incineration that was for a time a widespread method of solid waste disposal in high-rise buildings, the proposed system would be an immediate and efficient alternative to incinerators and would, therefore, be effective in eliminating existing on-site incinerators that are notorious polluters.[9] Another benefit to air quality results from the reduction of pollution from collection truck exhaust; the start-stop driving conditions of house-to-house collection are particularly productive of air pollutants. The proposed system would also elininate open burning of garden wastes in low density residential areas by providing an equally effective means of disposal. Ordinances prohibiting open burning are difficult to enforce, and numerous subterfuges are employed to circumvent such edicts.

By bringing all the combustible constituents of refuse to the treatment plant, open burning in dumps would be eliminated in practice as well as in theory. Against these benefits must be set the fact that incineration at the treatment plant to dispose of the very much greater sludge volumes will be more likely than at present. However, there is no reason why properly operated sludge incinerators would be any worse air pollutant emitters than the municipal refuse incinerators operated today; indeed, the tepee burners used by many small communities for incineration of refuse are notorious air polluters.[10]

Impact on the Visual-Aesthetic Environment. The impact of eliminating conventional refuse collection on the visual-aesthetic quality of the environment was examined in some depth by Nebiker and Meier.[11] They concluded that improperly stored refuse constituted one of the major elements in the vicious circle of urban poverty, environmental decay, and the demise of the older downtown urban areas in many of our large cities. Although this was primarily a public health consideration, unremoved solid wastes being a harborage of rats and other vectors characteristic of such areas, adaptation to the proliferation of unremoved rubbish leads eventually to an indifference to all aspects of environmental quality and especially its aesthetic quality. Cleaning up such areas would help greatly to restore dignity to those who live in our deteriorating residential areas. Even in other residential areas, immediate removal of domestic refuse would bring aesthetic benefits by eliminating unsightly storage.

Impact on Environmental Noise Levels. Existing refuse collection methods are a major source of noise. A recent study for the City of Chicago shows that nearly 10 percent of noise complaints received and investigated by the Department of Environmental Control under a new noise ordinance related to privately operated refuse trucks.[12] Reduction of the use of heavy trucks and the handling of metal containers would, therefore, reduce environmental noise levels. Against this must be set the increased noise from the grinding operation. However, being stationary sources, they are more easily shielded than nonstationary sources, and proper design should keep grinding noise to acceptable levels. In any case, grinders will have to be designed with the Federal noise regulations in mind, and it is anticipated that home appliances will shortly be limited to 80-85 decibels.

Socioeconomic Implications

Implementation of the proposed wet system for refuse collection would have numerous socioeconomic implications, not all of which are immediately apparent. Not all socioeconomic impacts are monetary, and those that are not are sometimes difficult to reduce to dollar terms. Nevertheless, these socioeconomic impacts may be of major importance in the overall evaluation of the wet system concept, and for reasons to be explained below, will be analyzed in detail in Phase II of the project. The following review is intended as a brief introduction to the types of issues and impacts that the complete socioeconomic assessment must consider.

Impact on the Labor Market. The proposed system would eliminate a large proportion of unskilled refuse collection jobs and increase the number of skilled jobs in industry for grinder and equipment manufacture and skilled jobs for treatment plant operators. Analysis of the impact of this shift on minority groups, traditionally the major source of unskilled sanitation worker labor, especially in inner-city areas where the system may have greatest tangible cost justification, will need careful consideration. However, economic hardships would be minimized if the collection work force were reduced gradually by normal retirement and departures. This would be consistent with an actual implementation program that would of necessity be phased over many years, and thus require a gradual rather than sudden diminution of the collection work force. The importance of avoiding drastic reductions in sanitation worker employment is documented by the experience of Cleveland, in which the collection force was reduced by some 600 men as a result of operational modifications.[13] In order to assess the impact of this reduction, one year later the city called over 300 of the individuals who had been laid off. Of the 300 men called, 200 phones had been disconnected, and of the 100 men that could be contacted, 97 were still unemployed.[14]

Both from a humanistic standpoint and from the economic viewpoint of increasing labor income, it is desirable that there be a shift toward skilled employment opportunities, and a wet system implementation should be coupled with an appropriate job training program where redundancies do occur. There appears to be little intrinsic social merit in retaining the menial employment opportunities of sanitation workers, and the virtual disappearance of almost an entire social class would not be unique. Domestic servants in the employ of the middle classes disappeared almost completely in the first half of this century with the radically changed social conditions of the immediate post-war era, and this in turn stimulated the introduction of labor-saving household appliances (dishwashers, washing machines, etc.). From this social viewpoint, the proposed system might, therefore, be considered eminently desirable.

Impact on Income Distribution. Traditionally, refuse collection service for residential communities has been financed from general tax revenues, the basis of which is the local property tax.[15] On the other hand, sewer system costs are often financed by service charges. These service charges, levied on a per household basis, are independent of household income, and the results are, therefore, more regressive[16] than if revenue was raised from just the property tax. Consequently, if these financing arrangements were not changed, implementation of a wet system would have an impact on income distribution as sewer service charges were increased[17] and the cost of conventional collection decreased.

Households not connected to a sewer line in an area where the proposed system is implemented will continue to require conventional refuse collection. The per household costs of such collection may be substantially higher because the economies of scale in conventional collection and disposal have been lost for the area as a whole.

A further consideration relates to the financing of the sewage treatment plant, which has had major Federal contributions in the form of construction grants.[18] Under existing aid schemes, these Federal contributions would be raised substantially due to increases in treatment plant construction costs where wet refuse collection systems are implemented.

Consequently, the net effect would be a shift from the more regressive local taxes previously used to finance conventional collection to the progressive Federal taxes, although partially offset by increases in the regressive sewer service charges. However, it is unlikely that existing arrangements would remain unchanged were wet system collection to be universally adopted; financing arrangements and equitable aid schemes must, therefore, be structured in such a manner that undesirable income distribution effects are avoided.

Although the above-mentioned considerations will vary considerably, both geographically and by income and housing groups, it is clear that the question of financing arrangements is important to the overall evaluation of the proposed system. One rational system of user charges would be to meter each user's discharge to the system;[19]

such metering may be desirable also on ground of equity as the nature and quantity of refuse varies so much from household to household. Moreover, such a system might be used to introduce marginal cost pricing, whereby households could be charged at a higher rate for increasing refuse discharges. This in turn might have the impact of reducing refuse generation rates via the pricing mechanism.

Impact on Public Health. By immediate disposal of all putrescible matter, there are clear benefits to local environmental sanitation. Disposal also of food packaging materials along with garbage would eliminate most potential food sources for undesirable rodents and insects in residential areas. As noted by David and Black,[20] rat infestations in residential areas are supported mainly on improperly stored garbage.[21]

However, there are some important public health consequences that are less obvious. Fecal wastes from domestic pets might introduce animal pathogens and intestinal parasites to wastewaters, although this might be judged as a net positive environmental effect as they would be treated at the treatment plant. Benefits will also accrue from elimination of a significant occupational health problem, since refuse collection workers have one of the highest injury frequency rates.[22] The concomitant reduction in medical services and output and leisure time losses may represent a significant social benefit. Moreover, implementation of a wet system would eliminate a considerable public health hazard at times of labor strike; had the prolonged 1968 sanitation worker strike in New York City taken place in summer, only drastic measures could have averted a major public health catastrophe.

A further social benefit can be identified to the aged and infirm. If a suitable grinder can be developed for installation in each and every residence (or by gravity or pneumatic chute access to a central grinder), it will no longer be necessary to carry full containers from the living unit to the point of curbside pickup. This would represent a real benefit to the elderly, especially those living in old, high density apartments without elevators.

Grinder safety is also a consideration of some importance to an evaluation of the overall public health impact. Some of the options to be studied in this research include that of a grinder installed in every home. These grinders would undoubtedly constitute what in legal terminology is defined as an attractive nuisance, and, consequently, they must be designed with child safety in mind.[23]

The possibility of toxic and nontreatable substances entering the environment may also have public health implications. But such substances may also enter the environment by existing solid waste management practices, and it is again the differential impact that is of interest to this evaluation.

Impact on Domestic Convenience. Finally, the trend toward domestic convenience must be recognized. The kitchen garbage grinder is purchased by households on the same basis as other household appliances are purchased, namely, because of the convenience it provides, and not because it is necessarily cheaper than garbage removal by conventional collection. Similarly, compacting devices for household refuse or for just garden wastes alone are now being marketed by several manufacturers, with the advertising emphasis on the convenience aspects. If a system for complete refuse disposal is marketed on the basis of domestic convenience, it may be that householders would be willing to bear the cost of the refuse grinder. In the overall economic evaluation, therefore, this is a factor that should be carefully considered.[24]

On the other hand, because it is by no means certain that metals and glass can be successfully transported in an existing sewer system, the alternative of excluding these materials must also be considered. But in the absence of a substantial decrease in the glass and metal content, a preliminary separation by the householder would be required, which detracts from the convenience benefits of the proposed system. In the case of metals, however, most grinder designs would allow these to be included in the charge without presorting, and the unground metals ejected from the grinder at the end of the grinding cycle.

Impact on Institutional Arrangements. The wet systems concept, by replacing conventional house-to-house collection by transport in the sewer system, calls for a shift from the private to the public sector in the many urban areas where refuse collection is undertaken by private contractors. As such, it would be naive to suppose that the elimination of the highly profitable collection contracts would not engender strong political opposition from the former recipients.

A second institutional problem would doubtless arise from the collection worker unions. During the transition phase, when conventional collection would coexist with the wet system, any union opposition to the concept could have powerful impact, both politically as well as practically by use of the strike weapon. This possibility stresses the need to consider very carefully the impact of the wet system on the collection worker who would lose his existing job, and the vital necessity of avoiding redundancies.

Another potential source of institutional problems would spring from the municipal power structure itself; where refuse collection and sewers and sewage treatment are organized under separate departments, the virtual dismantling of the refuse collection departments, and significantly increasing the size of the sewer department may well strain departmental loyalties to the point of outright opposition.

Review of Previous Research

The concept of wet systems for residential refuse collection has been previously studied by several university investigators and government funded research contractors. There is also a considerable body of research on pipeline systems for refuse transport that have as their prime focus not the collection of refuse, but the transportation of refuse from a few centrally located collection centers to the site of disposal. Much of this is directly applicable to the goals of this study.

All of the work referenced in this section will be discussed in much greater detail in later sections of the report and should not be regarded as an exhaustive literature review. The intent here is to give the reader an outline of the state of existing knowledge on the subject so that the objectives of this study, as outlined in the next section, are fully understood.

Research on Wet Systems for Residential Refuse Collection. The first to investigate the feasibility of using sewers for refuse transport and joint refuse-sewage treatment was the Los Angeles County Sanitation District, which conducted experiments with ground refuse in large interceptors in July 1963.[25] It was concluded that the idea was probably feasible, but not pursued further because of anticipated problems at the treatment plant, the most important of which being a 25 fold increase in sludge volume.

The next to study the idea was the ASCE Combined Sewer Separation Project. In a report published in February of 1968, the idea of including ground refuse in pressurized sewers was examined, but no experiments were conducted.[26] Independently in 1968, Nebiker and Meier[27] analyzed the idea from a social and environmental viewpoint, and they concluded on the basis of some preliminary cost/benefit estimates that the idea should be further pursued.

In 1970, Etzel[28] suggested the use of hydropulpers, widely used by the pulp and paper industry, as a means of refuse size reduction prior to discharge into the sewers. Etzel also suggested some radical changes at the sewage treatment plant, including the use of advanced waste treatment processes such as reverse osmosis to treat the high solids loadings that would result.

The first detailed research study was conducted by Foster-Miller under contract to EPA.[29] The objectives of this study were to evaluate the feasibility of hydraulic transport of ground refuse in existing sewer lines by experimentation in a section of straight sewer pipe, and to evaluate the feasibility of treating a sewage-refuse mixture at a conventional sewage treatment plant by laboratory analyses of sample refuse-sewage slurries. However, because the hydraulic experiments used water rather than sewage, and because limited treatment experiments were conducted, technical feasibility was not unequivocably demonstrated.[30] In a second phase, Foster-Miller developed a preliminary design for a household refuse grinder. Experiments during this second phase showed that refuse was amenable to size reduction in small, low-powered slurry grinders and that the few components that were not easily ground constituted a relatively small weight and volume fraction of the total domestic refuse.[31]

McKinney and Mahloch[32] examined the costs of the concept in late 1971 and concluded that at the present time, conventional collection was more economical. They stressed, however, that increased labor costs for refuse collection, improved wastewater treatment methods, and the successful development of grinders[33] would very likely make grinding and discharge to the sewers the preferred method.

In 1971, the Brookhaven National Laboratory[34] planned a three-year, $800,000 study for the Atomic Energy Commission to demonstrate the feasibility of the concept, followed by a $2.2 million study to investigate resource recovery at the treatment plant. The Brookhaven concept envisaged the use of neighborhood pulpers and transportation in sewers to a treatment plant which would recover paper fiber, glass and metals and use pyrolytic treatment for the remaining constituents. The goal was an effluent of sufficient quality for aquifer-recharge. This planned project, however, was never funded.[35]

A second contract was let by EPA to Foster-Miller to study the feasibility of hydraulic transport of refuse in sewer appurtenances and other potential problem areas in sewer systems (siphons, manholes, T-junctions, bends, etc.). Again, water rather than sewage was used as the transport medium. However, the results of this research did indicate some potential problems, and will be discussed at length in later sections of this report.

Finally, in late 1972, Courtney and Sexton compared the sewer transport concept against pneumatic and pressurized alternatives. They concluded that sewer transport appeared particularly suitable for existing urban areas.[36]

Other Pertinent Research. The area of research that is most directly related to the wet system for refuse collection is that of pipeline transport of refuse. However, the emphasis has previously been on hydraulic transport from centrally located collection points to the ultimate disposal site, as an alternative to truck or rail haul, rather than eliminating house-to-house collection.

Of all the alternative pipeline systems considered to date, slurry transport has received most attention. This calls for refuse to be ground and mixed with sewage or water and conveyed under pressure as a slurry of between 6 and 12 percent solids content. However, several other pipeline concepts have been considered, including hydraulic transport of briquettes and slugs.[37]

The slurry pipeline idea has been pursued by Zandi and co-workers at the University of Pennsylvania for many years, and extended to include a vacuum system to bring refuse from the individual home to the neighborhood stations where the refuse is ground and injected into a slurry pipeline network.[38] This combination is therefore a direct competitor to the proposed system, in that it completely replaced conventional collection. Pipeline transport of shredded solid waste has also been investigated by researchers at the Western Company, who have proposed the use of friction-reducing polymer additions to increase pipeline capacity.[39]

In the area of grinding, we must turn to recent developments in the pulp and paper industry, for the latest generation of hydropulpers appears to be eminently suited to the size reduction of paper-rich solid waste. The experience of the paper industry is also very important to an assessment of treatability. For many years it has worked in treating cellulose and fiber-rich wastes by technologies similar to sewage treatment, and with special emphasis on recovery.[40] In particular, screening is a technology well developed in the paper industry that is suitable as a modfiication to existing treatment plants for solids removal in preliminary treatment. This and other paper industry treatment technologies will be carefully assessed in the technical evaluation of this report.

The feasibility of treating refuse slurries by technology adapted from the paper industry is currently under study at a demonstration project at Franklin, Ohio.[41] Designed by the Black-Clawson Company for 150 tons of municipal refuse per day, the objective of the treatment plant is to recover metals, glass and paper. The first step in the treatment process is to pulp the incoming refuse in a hydropulper, using recycled process water and chlorinated secondary effluent from an adjacent wastewater treatment facility. Although a sewage-refuse slurry would require some substantial modifications in the treatment process configuration, the proposed system of wet collection of residential refuse appears to be entirely compatible with these latest efforts toward resource recovery from municipal solid wastes.

Objectives of this Research

It is clear from the foregoing review that although there exists substantial literature on the subject of wet systems for residential refuse collection, no data on treatment or transport of refuse-sewage mixtures in real situations are available. Moreover, most of the economic analysis of the concept has been superficial, depending on very gross estimations of the costs involved. And while the Foster-Miller work has yielded valuable information on the hydraulic transport aspects and on grinding, very little throught has been given to the problems at the sewage treatment plant. Many who have analyzed the latter question have concluded that although feasible, primary treatment and sludge disposal facilities of existing treatment plants would be overburdened with concomitant increases in treatment costs. Yet there are some obvious modifications and additions to preliminary treatment that might avoid these problems, and these have yet to be examined.

Above all, there has been no comprehensive, systematic technical and economic feasibility study, and it is this gap that this research seeks to fill. There is a need for a systematic investigation of the cost trade-offs between conventional and wet system collection and between variations of the wet system itself over a wide range of conditions. There is a need to cost out an implementation of a wet system in a real situation, and thereby substitute detailed cost estimates for the crude estimates of the existing literature. There is a need to bring the socioeconomic, institutional and environmental impacts into the overall cost-benefit evaluation of the concept. There is a need to review the impact on the sewer system and treatment facilities in a comprehensive fashion, so that the potential problems are anticipated and further research priorities clearly identified. And finally, there is a need to answer the question of where do we go from here? Are further laboratory and bench-scale studies needed before proceeding to a pilot demonstration study, and if so, which are the critical questions yet to be answered? Are there some easily conducted and inexpensive field demonstrations that could shed further light on questions unanswerable from a desktop perspective?

These, then, are the questions that this research seeks to answer. But it will soon be apparent that definitive answers to many questions are not possible at this point in time, and to that extent, this research has the additional goal of ensuring that all possible questions have indeed been raised, even if not completely resolved.

Review Panel

Because of the multi-disciplinary nature of the work to be undertaken, and because of the complexity and controversial nature of many of the concepts introduced in this evaluation, a panel of expert consultants was formed to review and discuss the findings of the contractor on a regular basis during the conduct of this study. The panel was constituted to reflect as many of the potentially conflicting viewpoints as possible; its membership is identified in the acknowledgments section. Six discussion meetings were held during Phase I and the panelists also made substantial review contributions to this written report.

REFERENCES

CHAPTER I

1. Clark, R., "Urban Solid Wastes Management: An Economic Case Study," EPA Environmental Protection Series EPA-R2-73-012, Aug. 1972.

2. *Ibid.*, p. 19.

3. The Romans, of course, had magnificient sewer systems; the Cloaca Maxima was completed by Tarquinius Superbus in the 5th Century B.C.

4. These experiments are discussed in some detail in Chapter III.

5. Downing, P., "The Economics of Urban Sewage Disposal," Praeger Special Studies in U. S. Economic and Social Development. Praeger, New York, N.Y., 1969.

6. Conventional collection is used in this report to describe house-to-house surface collection by truck.

7. Note that economies of scale *decrease* average per unit costs when *increasing* total plant capacity, and *increase* per unit costs when *decreasing* total plant capacity.

8. A recent EPA survey concludes that 50 percent of the solid waste generated in the U. S. is burned by some means, including both open and enclosed burning. See "Compilation of Air Pollution Emission Factors," EPA Office of Air Programs, Research Triangle Park, North Carolina, February 1972, p. 2-1.

9. In all fairness, it should be noted that this is not necessarily an inherent characteristic of on-site incinerators. Poor maintenance, improper operation and design deficiencies are generally the causes of excessive pollutant emissions.

10. Kreichelt, T. E., "Air Pollution Aspects of Tepee Burners Used for Disposal of Municipal Refuse," U. S. Public Health Service, Division of Air Pollution, Publication 999-AP-28, September 1966.

11. Nebiker, J. and P. Meier, "Hydraulic Disposal of Solid Wastes," *Proc.* 1st Annual Northeastern Regional Anti-Pollution Conference, University of Rhode Island, Kingston, R. I., July 1968.

12. "Noise Facts Digest," Report by Informatics, Inc. to Office of Noise Abatement and Control, EPA, Washington, D.C., June 1972, p. 3.

13. See Clark, R. M., and J. Gillean, "Systems Analysis and Solid Waste Collection," EPA National Environmental Research Center, Cincinnati, Ohio, March 1973.

14. Personal communication with R. M. Clark of the EPA National Environmental Research Center, April 16, 1973.

15. See for example, Clark, R., and R. O. Toftner, "Financing Municipal Solid Waste Management Systems," J. San. Eng. Div., ASCE, 96, SA4, p. 885, August 1970.

16. That is, low income households pay a higher percentage of their income than do high income households.

17. An increase would be almost inevitable as a result of increased sewer maintenance and repair costs; see Chapter VI.

18. For a detailed discussion see also Loop, W. J., "Alternative Methods of Financing Waste Treatment Facilities," J. WPCF, 42, 2, p. 291, February 1970, or I. A. Johnson, "Division of Cost Responsibility for Wastewater Systems," J. WPCF, 42, 3, p. 341, March 1970.

19. This problem of metering is discussed further in Chapter II.

20. David, P. L., and R. J. Black, "Effects of Garbage Grinding on Sewage System and Environmental Sanitation," APWA Reporter, December 1962.

21. But note than even though the surface rat population would decrease, the rat population of the sewers would increase. Nevertheless, the net effect is judged by Public Health Experts to be positive (personal communication, Dr. Howard Peters, Professor of Public Health, University of Massachusetts, November 1972).

22. 62.2 injuries per million man-hours worked as opposed to 12.1 for manufacturing and 34.5 for the contract construction industry.

23. In addition to some form of interlock to prevent start up with an unlocked cover, a two-hand starting switch might be considered.

24. One method of quantifying such benefits is to evaluate communities with no municipal refuse collection and where residents are required to bring their refuse to the disposal facilities themselves. In such communities, there are often residents who pay between 50 and 100 dollars per year to private contractors to perform this inconvenient task.

25. Two unpublished memoranda report on the results on these experiments; one dated September 13, 1963, entitled "Report on a Study of the Feasibility of Disposing of Rubbish into a Sewage Disposal System," the other dated May 26, 1965, by R. Whitley, is entitled, "Evaluation of Settling Characteristics of Ground Refuse in Sewage."

26. Waller, D. H., "An Examination of the Benefits and Disadvantages with Respect to the Disposal of Solid Wastes," ASCE Combined Sewer Separation Project, Technical Memorandum No. 10, February 1968.

27. Nebiker, J. and P. Meier, op. cit.

28. Etzel, R., "One System Treats Sewage and Solid Waste," Chemical and Engineering News, March 23, 1970, pp. 44-45.

29. Contract CPE-70-115, originally let by the Bureau of Solid Waste Management, Environmental Control Administration, Department of Health, Education and Welfare, in June 1970.

30. None of the Foster-Miller reports have yet been published; they are available from The EPA Solid Waste Research Laboratory.

31. This design is reviewed in detail in Chapter II.

32. McKinney, R., and J. Mahlock, "An Economic Evaluation of Garbage Grinding Versus Surface Collection and Disposal," Water and Sewage Works, Reference Number, November 1971.

33. The authors were apparently unaware of the Foster-Miller Research and of recent developments in the pulp and paper industry.

34. McGraw-Hill's 1972 report on Business and the Environment, pp. 6-7.

35. Personal communication with Mr. Maxwell Small of Brookhaven National Laboratory, November 1972.

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37. "Pipeline Transportation of Solid Waste," report by the Stanford Research Institute to Bureau of Solid Waste Management, Environmental Control Administration, Department of Health, Education, and Welfare. (Contract PHS-1-DO-1-U1-00208-01) February 1971.

38. Zandi, I., and J. Hayden, "A Pneumo-slurry System of Collecting and Removing Solid Wastes" in Zandi, I., Editor, Advances in Solid-Liquid Flow in Pipes and its Applications," Pergamon Press, N.Y., 1971.

39. See "Pipeline Transport of Shredded Solid Waste," Report by the Western Company to the EPA Solid Waste Management Program, 1971, open-file Report SW-36C, and Overfield, J. L. et al., "Increasing Wastewater Flow Velocity Using Chemical Additives," J. WPCF, 41, 9, p. 1570-1585, September 1969.

40. See for example, Bishop, F. W., and A. E. Drew, "Disposal of Hydrous Sludges from a Paper Mill," Journal of the Technical Association of the Pulp and Paper Industry, Volume 54, No. 11, (November 1971), pp. 1830-1832.

41. See for example, Herbert, W., "Recycling Municipal Waste," Chemical Engineering, January 10, 1972, p. 66-67.

CHAPTER II

GRINDING

Introduction

Insofar as the focus of this study is the analysis of total systems for wet collection of residential refuse, the technical details of the suggested designs for the individual engineered components are of less importance than the interrelationships between system components and the environment in which the components function. Moreover, there exist several excellent discussions on the technical aspects of grinding domestic refuse for wet collection systems, notably the studies by Zandi[1] and by Fisk and Guzdar,[2] to which the reader interested in the design aspects and the performance of available commercial equipment is referred. Indeed, since it is one of the major goals of this study to develop the range within which grinder costs must lie for a wet system to be competitive with existing and alternative collection systems, and to establish the optimum working conditions for the total system, the emphasis of this chapter will be to analyze the grinding subsystem in the perspective of total system requirements. We shall discuss how the design concepts and design specifications are dependent on other system components, relationships that will be quantified in the economic analysis of later chapters. We shall also analyze how future trends may affect grinder design specifications; for example, any substantial future reduction in metal and glass content of refuse would greatly ease the mechanical engineering problem of designing small units suitable for installation in individual living units.

Dependency of Grinder Design on Housing Type. The effect of the economies of scale in grinder capital and operating costs on the overall economic viability of the wet system approach to refuse collection was apparent in the early stages of the research. It was also clear that the choice of type and size of grinder (or other pre-treatment device) was closely related to the type and density of housing. In other words, the type and size of grinder selected for a low-density single family residential area would be very different to that selected for a high-rise apartment building. Therefore, the discussion of the grinding options is framed in terms of the three basic locational alternatives; one grinder per living unit, one grinder per structure, and one grinder per group of structures (i. e., per block or per neighborhood).

Garbage Grinders. The future fate of the in-sink kitchen garbage grinder in households where a refuse grinder would also be present was raised at one of the consultant panel meetings. Fortunately, the inability to make accurate predictions of consumer preferences on this point is not serious, and indeed, we shall exclude the question from further consideration for the following reasons. Firstly, since a grinder that can handle the other refuse components can automatically handle garbage, including or excluding garbage from the refuse grinder (because it is or is not ground elsewhere in the kitchen sink garbage grinder) will have little or no impact on the choice of refuse grinder design. Secondly, the expected disparity in cost between a garbage and refuse grinder is so great, the initial cost of the latter being 10 to 20 times that of the former, that the decisions to purchase these items can be considered as being independent of each other. Householders may still wish to purchase a garbage grinder on convenience grounds alone, even if a refuse grinder, which will be a necessity rather than a convenience if conventional collection service is discontinued, is already present. This reasoning is no different to that which may be applied to the existing situation, in which garbage grinders co-exist with conventional collection.

One Grinder Per Living Unit

Technical Feasibility. The technical feasibility of grinding refuse in the individual home was examined by Fisk and Guzdar[3] as part of the initial contract with EPA, and a conceptual design for a grinder suitable for installation in the individual home was developed as part of this work. The desirability of a wet grinding process was quickly established for several reasons. First, water reduces the strength of the major component, namely paper, resulting in lower power requirements. Second, noise and dust are appreciably reduced by the presence of water. Finally, the much higher viscosity of a liquid system reduces the mobility of the contained solids,[4] thus increasing the effect of shear forces produced by equipment components, which in turn increases grinder efficiency. Batch feeding of refuse was chosen for reasons of fully exploiting attrition effects and the fact that householders are familiar with batch operations.

Interaction with the User. To ensure that the grinder is accepted by the user, the design was chosen to parallel that of other household appliances such as washing machines, clothes dryers, etc. Controls, safety devices and operating procedures are similar, utilizing the homeowners' experience and respect for such electro-mechanical devices.[5] Inconvenience and high repair costs are the incentives for the householder to respect the device and to discourage the continued feeding of items liable to cause problems, such as wire-type metal coat hangers used by dry cleaning establishments.

Design Constraints. One of the major difficulties is that of providing adequate power given the limitations of 230-volt service generally available. It was concluded on the basis of experiments that size reduction of steel cans would probably be beyond the power requirements of a grinder limited to 230-volt service; the design finally proposed utilized a 2 HP motor in full recognition that not all constituents would be ground. The grinding mechanism selected uses a high speed, high clearance shear, with no meshing parts.[6] While steel, heavy gauge aluminum and certain ductile plastics could not be ground, the design was such that nongrindables would not cause machine-jams. These nongrindables would remain in the grinder at the end of the 12-minute grinding cycle, cleansed of any putrescible matter by a freshwater flushing cycle, and easily removed from the grinder. An artist's impression of the design is shown on Figure 1 and further details can be found in the quoted report.

Exclusion of Refuse Constituents. The exclusion of steel and heavy gauge aluminum is not judged serious, and may be necessary anyway because of difficulties in hydraulic transport in gravity sewer systems. A preliminary concept for a high power grinder capable of grinding metals was examined by Fisk and Guzdar,[7] but numerous technical problems were forecast. Moreover, the metal nongrindables would be free of putrescible matter, and of relatively small volume; laboratory tests indicated that even nongrindable cans would be considerably compressed. Storage until infrequent conventional collection would thus be feasible. Finally the nongrindable metals would be clean (paper labels and paint would be removed during grinding, for example), and thus represent a much better raw material for metal recovery than an existing refuse from which nonmetals must first be separated. We shall return to the impact of the exclusion of steel from household grinding capability on the total system in several subsequent chapters; what is involved is a trade-off between the high additional costs of a grinder accepting steel and the costs of disposing by conventional means the nongrindables of the relatively cheaper grinder that does not grind steel.

The Source of Grinding Water. A major problem at this scale concerns the source of water for the wet grinding process, as dry grinding processes must be rejected as an alternative. Originally, Nebiker and Meier[8] suggested the use of freshwater for this purpose, and grinding at a solids content sufficiently high to keep increases in freshwater consumption to acceptable levels. Foster-Miller, on the other hand, have investigated grinding at 1 percent solids and less, i.e., at the same concentration as is necessary for transport in sewers built to existing design standards At 1 percent solids concentration, about 12 gallons of water are required per pound of solid waste, or 30 gallons for an average generation of 2.5 pounds per capita per day. If this water were taken directly from the freshwater supply, it would represent a major increase in freshwater consumption, and a concomitant increase in sewage flows. This is undesirable on both counts, and, therefore, Foster-Miller investigated the reuse of nonfecal wastewater as a source of grinding water.[9] This involves a plumbing separation of all wastewater except water closet effluent to a storage tank, from which grinding water is drawn as needed. One suggested configuration of this concept is illustrated on Figure 2. However, this involves a very high installation cost for the plumbing modifications, especially in existing housing. Indeed, as indicated on Tables 1 and 2, these costs are so high, exceeding in some cases by a multiple the cost of the grinder itself, that the Nebiker-Meier concept remains an alternative that merits serious consideration. This would involve grinding at

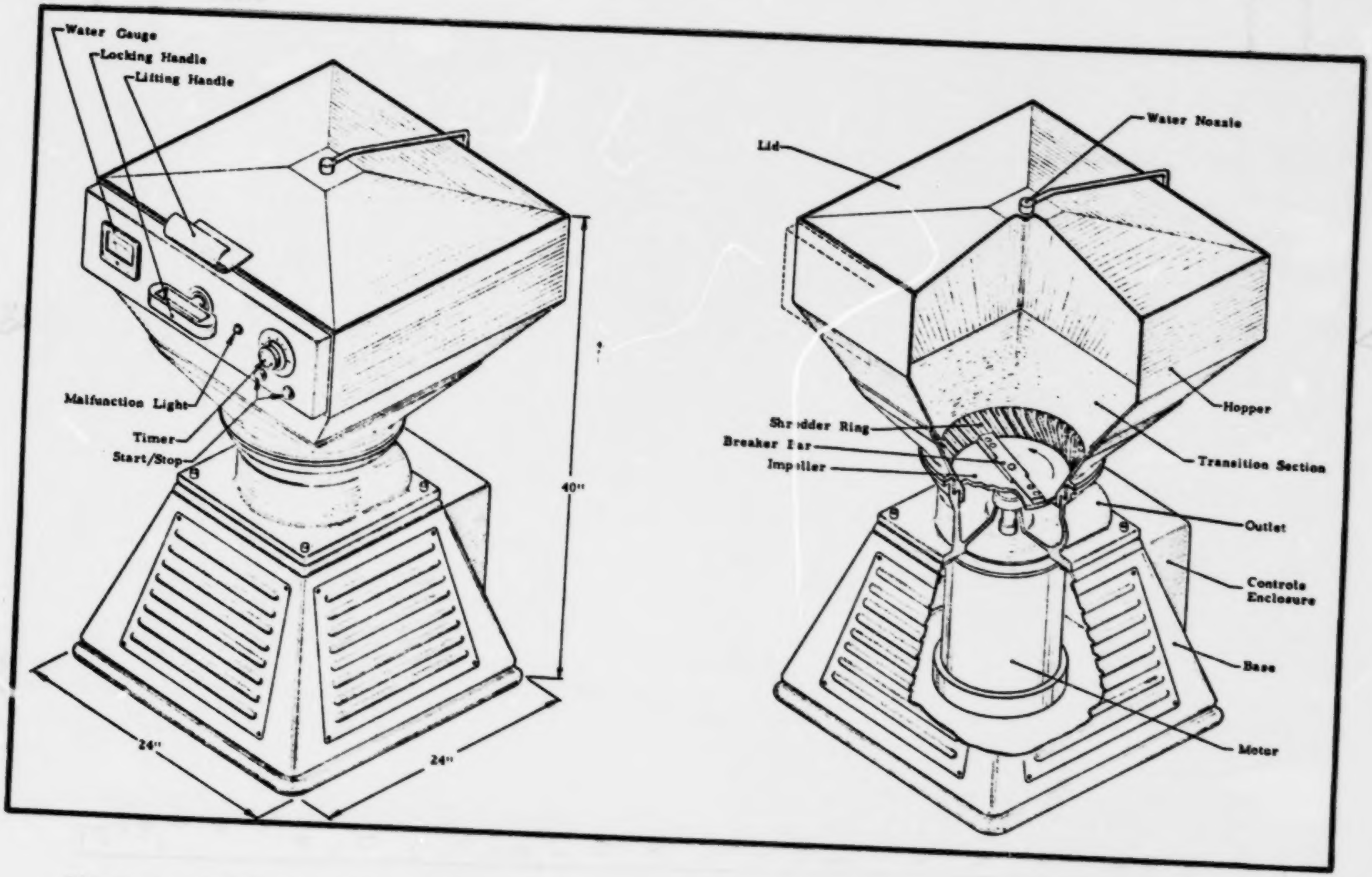
Water Gauge
Locking Handle
Lifting Handle
Malfunction Light
Timer
Start/Stop
40"
24"
24"
Lid
Water Nozzle
Hopper
Shredder Ring
Breaker Bar
Impeller
Transition Section
Outlet
Controls Enclosure
Base
Motor

Figure 1: Preliminary Design for a Household Grinder (Source: Fisk & Guzdar, op. cit., page 83)

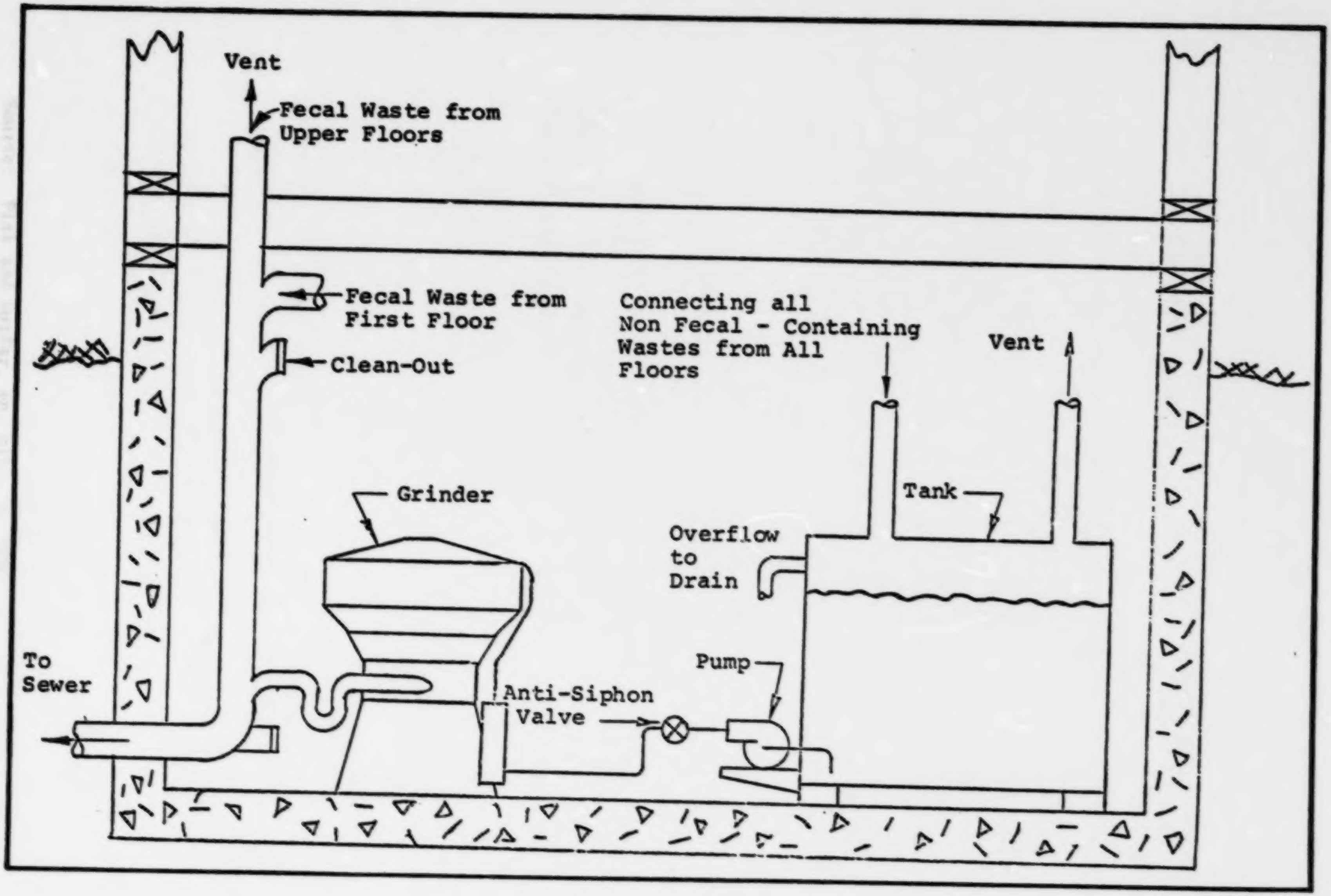
Vent
Fecal Waste from Upper Floors
Fecal Waste from First Floor
Clean-Out
Connecting all Non Fecal - Containing Wastes from All Floors
Vent
Grinder
Tank
Overflow to Drain
To Sewer
Pump
Anti-Siphon Valve

Figure 2: Basement Installation of a Household Grinder (Source: Fisk & Guzdar, op. cit., page 32).

Source: Fisk and Guzdar, op. cit., p. 32.

Table 1: House Modification Costs for a Typical Residential Refuse Grinding System.

Type of House Construction	Cost Using Copper Pipe, $	Cost Using PVC Pipe, $
New two story slab type	494.00	275.00
New two story basement type	432.00	215.00
New one story slab type	397.00	233.00
New one story basement type	337.00	173.00
Existing two story slab type	1,211.00	1,057.00
Existing two story basement type	799.00	645.00
Existing one story slab type	1,085.00	935.00
Existing one story basement type	673.00	523.00

Source: Fisk and Guzdar, op. cit., p. 101.

Table 2: Estimated Manufacturer's Cost of Proposed Household Refuse Grinder System.

	500 Units Total	20,000 Units Total
Basic Grinder, complete with:	$ 592.00	$ 180.00
Base, motor, grinder section, hopper and lid, electrical controls and starter, safety devices, sound attenuation, tooling, and assembly		
Water Storage System, complete with:	275.00	116.00
Tank, pump and motor, level switch and gauge, manual and automatic valves, overflow provision, vent, service connections, and assembly		
Installation[a]	200.00	150.00
Total Manufacturer's Cost	$1,067.00	$ 446.00
Selling Price[b] (Cost x 1.75)	$1,867.00	780.00

[a] Does not include possible increase in electrical service.

[b] Add $250 for outdoor tank (slab construction).

Source: Fisk and Guzdar, op. cit., p. 100.

much higher consistencies, between 5 and 10 percent solids, requiring in turn only 3 to 6 gallons per 2.5 pounds of refuse, and pumping the resultant slurry to the street sewer. This pressurization of the building connection would be necessary because of the much higher solids load. But once the street sewer is reached, the dilution provided by its normal flow would bring average concentrations back to the 1.0 percent required to avoid deleterious impacts on the sewer system. The trade-off is, therefore, between the cost of plumbing modification and storage tank of the Foster-Miller concept and the cost of a pressurized building connection and pump of the Nebiker-Meier concept. But as we shall see in Chapter VI, the cost of the pressurized building connection, even though considerably less than the plumbing modification, is nevertheless still very costly.

However, two further advantages in favor of the Nebiker-Meier concept can be stated. First, at higher consistencies, the grinding process is much more efficient because of the matrix effect and because of the smaller volume to be treated, which in turn results in a power saving and improved grinding efficiency.[10] Second, the higher consistencies are much more effective in dampening noise. A possible problem of the Nebiker-Meier idea is that of mixing in the street sewer at the building connection. Provided the street sewer is at least one quarter full, and flowing at sufficient cleansing velocities, stratification can probably be avoided, and because refuse will in all probability be ground during times of peak sewer flows,[11] this may not be serious. Furthermore, because the building connection must be cleared after each pumping cycle to remove the slurry remnants, and the grinder cleaned, a rinse of about 20 gallons per load will be required. This flushing might prevent stratification downstream of the building connection, but also brings the total water requirement back to between 30 and 40 gallons per household per day, which would represent a sizeable increase in total average water consumption.

Re-Use of Laundry Effluents. One possible way to diminish the freshwater requirement is to use washing machine effluent as a source of water for either flushing or grinding or both. This source of water would provide between 200 and 500 gallons per household per week,[12] which would reduce the freshwater requirement substantially, if not entirely. The idea is feasible on the assumption that any single family home with a refuse grinder would surely also be equipped with a washing machine. The first of these assumptions is readily established by examination of the 1970 Census of Housing, with some selective results shown on Table 3. Washing machine effluents are almost universally pumped from the machine by means of a rubber hose, and to connect this hose to the grinder would involve little or no replumbing. As is common practice in the paper industry, the grinder would also act as a water storage tank, with the refuse load being added to the full charge of water; hence the need for the additional storage tank might be eliminated. If more water were available from the washing machine than to provide for one charge of refuse, the excess would then be pumped (by the grinder pump) to the sewer, thus providing frequent flushing. Using washing machine effluent for flushing is particularly effective because the high detergent content and the elevated temperature will be much more effective for thorough cleaning of the system than would cold freshwater. It might be added that modern dishwater and washing machine detergents do not contain foaming agents, which are added to nonappliance detergents for aesthetic rather than efficiency reasons.

A potential obstacle to this idea is that the use of laundry effluents is also under study for flushing toilets, an idea currently under investigation by an EPA contractor.[13]

Table 3: Washing Machines in Selected Massachusetts Communities

Town	Single Family Units as Percent of all Living Units	Percent of all Living Units with Washing Machines	Persons Per Household
Acton	73.6	77.7	3.67
Billerica	88.1	88.1	3.91
E. Longmeadow	94.8	88.9	3.51
Longmeadow	98.1	86.0	3.47
Peabody	65.2	76.6	3.38
Tewksbury	94.3	90.8	4.13
Wilbraham	93.4	94.2	3.61
Pembroke	96.0	94.0	3.63
Sudbury	95.1	96.0	3.87
N. Bridgetown	43.2	81.0	3.18
Hanover	95.5	90.0	3.94

Source: U. S. Census of Housing, 1970

Potential Limitations of the Wastewater Re-Use Concept

Questions have been raised as to the feasibility of the Foster-Miller concept in the light of recent information on per capita refuse and sewage generation rates in the single family residential areas that are the most likely candidate for living-unit grinder installation. In particular, the possibility of there being too little reusable wastewater for grinding at less than 1 percent solids must be examined in some detail, and a discussion of the most recent data is deemed appropriate in order to develop some representative assumptions.

Quantity of Residential Refuse. There exists considerable confusion in the literature as to the quantity of refuse generated in residential households. The consensus holds that 5 pounds per capita per day in an urban area is a representative figure, and the Foster-Miller grinder design was based on this generation rate.[14] However, the latest data collected by the Data Acquisition and Analysis System of the EPA Solid Waste Management Office suggests that this figure is far too high for residential areas.[15] Figure 3 shows the per capita generation rates of 23 collection routes during the period January through February 1972. These 23 routes were distributed in 5 metropolitan areas,[16] and chosen to represent a wide range of socioeconomic and climatic conditions. A representative average figure appears to be about 2.25 lb/cap/day. Although one must also be concerned with extreme conditions if universal installation is anticipated, 92 percent of all residential collection surveyed had rates lower than 4.5 lb/cap/day.

Quantity of Sewage. Similar confusion appears to exist over the quantity of sewage produced by the individual home. The 100 gal/cap/day figure that is used as a basis for sewage treatment plant design capacity is clearly inappropriate as a figure for sewage production by an individual residence; it includes, for example, a substantial allowance for infiltration. Other estimates for residential rates suggest about 50 to 60 gal/cap/day.[17] But again, examination of the most recent data suggests that a representative figure for single family homes is even lower. At an EPA Pressure Sewer Demonstration Project in an Albany, New York, suburb, actual average rates for 12 townhouses were found to be in the order of 30 to 40 gal/cap/day, with a maximum of 48.5 and a minimum of 20.9. As was noted in the Project Report,[18] this low figure may be due to the fact that 75 percent of the residents were children of school age (as against 34 percent for the New York State average).[19] But a single family home is precisely where one expects to find families with children of school age, and, consequently, a range of 30 to 50 gal/cap/day appears to be a good figure upon which to base a choice of grinder option.

Quantity of Wastewater Available for Grinding. The source of grinding water for the Foster-Miller design is "used domestic water not containing fecal waste, etc."[20] It is not clear from the Foster-Miller report what fraction of total wastewater would thereby be available for grinding; but even a conservative estimate of 85 percent of total wastewater would only yield between 25 and 43 gals/cap/day on the basis of the figures established in the previous paragraph. Using a refuse generation rate of 5 lb/cap/day implies a grinding consistency of between 1.39 and 2.5 percent. In other words, if the 5 lb/cap/day figure were correct, then the reusable wastewater would not suffice to grind at 1 percent. This is important because at concentrations about 1.5 percent, the friction head loss reduces sewer capacity, and a presurized building connection would be needed to prevent blockages. Yet, if freshwater were used to make up the deficiency, the intent of the reuse concept would be compromised, and under such conditions, one might prefer to grind at the high consistencies of the Nebiker-Meier concept and save the considerable cost of replumbing. Fortunately, a more realistic figure for refuse generation is in the neighborhood of two pounds per capita per day in such areas where living-unit grinders are appropriate; this results in a grinding consistency of from 0.55 to 1.00 percent. Consequently, we conclude that the Foster-Miller conceptual design involving the reuse of domestic wastewater for grinding water is presently feasible even under the conditions that the very latest data reveals for single family residential areas.

Institutional Constraints. Several panel members were of the opinion that there would be considerable resistance against the Foster-Miller reuse concept from public health interests. The possibility of a cross-connection is very real because a freshwater line must also be connected to the grinder for the flushing cycle.

Impact of Future Trends on Grinder Options

The Nature of the Problem. Although both alternative concepts for the living unit grinder appear feasible at the present time, future developments in refuse production and water consumption may impose some severe constraints on the design flexibility that presently exists. An increase in per capita refuse generation rate of 1 or 2 percent per year is expected by most observers; a trend which will increase the grinding water requirement given a constant grinding consistency. On the other hand, efforts at reducing water consumption, and therefore wastewater production, are receiving even greater emphasis, and any widespread reduction in sewage production would further reduce the potential for reusing wastewater as a source of grinding water in the individual home.

Note that even though *average* per capita water consumption may be on the increase in urban areas, much of the increasing demand in residential areas is for purposes such as lawn sprinkling, humidifiers, car washing and the like, all of which do not result in increased sewage production. And, of the major wastewater-producing appliances, washing machines are already installed in most single family homes, as noted on Table 3. On the other hand, devices such as shallow-trap toilets and flow restricting shower heads[21] may well offset the increase in wastewater production from other sources, such as increased use of dishwashers. The possibility of a reduction in per capita sewage production in residential areas sometime in the future is therefore far from academic.

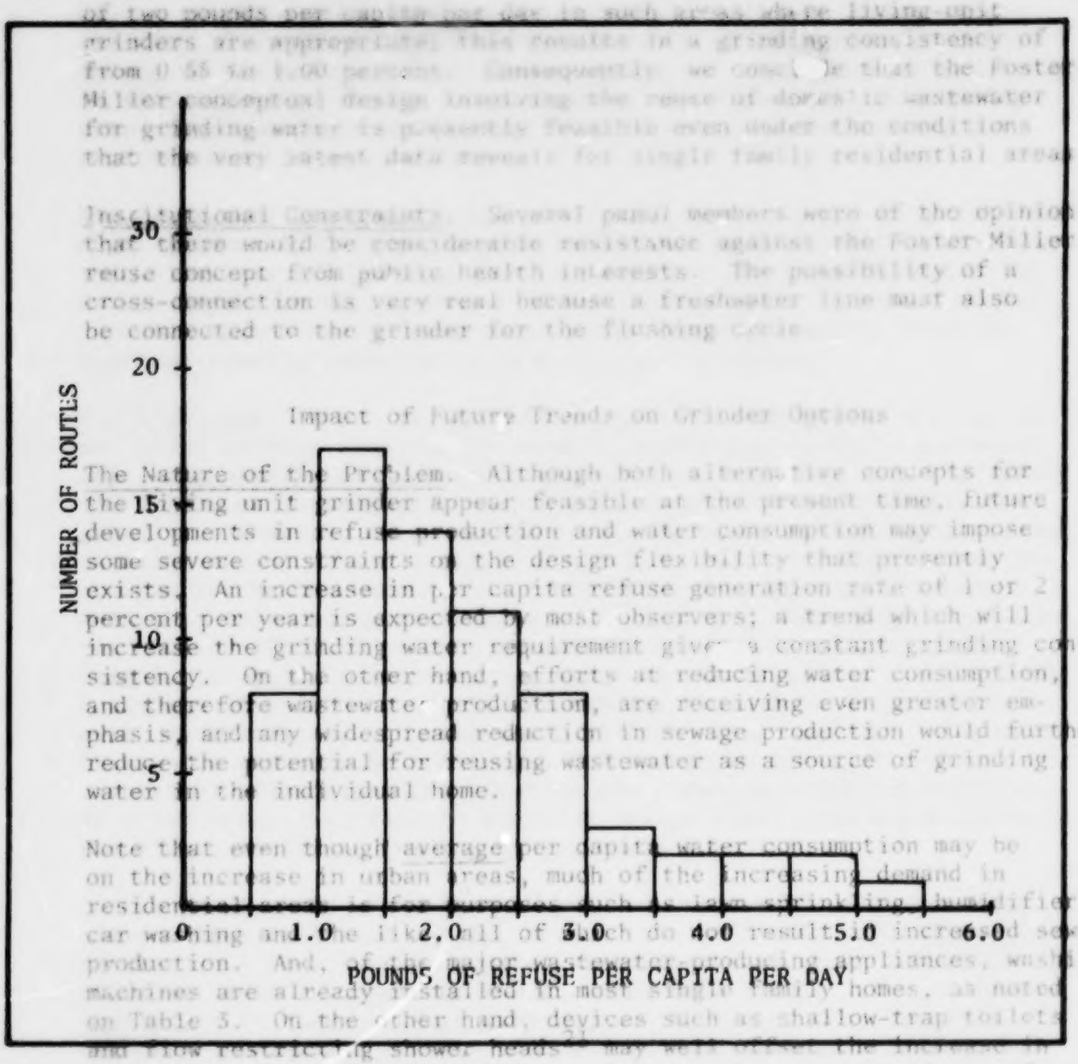

Figure 3: Histogram of Per Capita Refuse Generation in Residential Areas

The impact of any increase in refuse loadings and a decrease in reusable wastewater on grinder design flexibility can be examined by considering the interrelationship between refuse generation, grinding consistency, and grinding water requirement, which is given by the following equation:

$$Q_{GR} = \frac{L_R(1 - \Omega - \lambda)}{8.34 \lambda}$$

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where q_{GR} is the gallons of water required for ginding per capita per day, λ is the grinding consistency ($o<\lambda<1$), i.e. the solids weight fraction, Ω is the moisture weight fraction of the refuse ($o<\Omega<1$), and L_R is the pounds of refuse per capita per day. This relationship is illustrated on Figure 4, which shows the dependence of grinding water requirement on minimum grinding consistency for varying per capita refuse gneeration rates.

Recalling that average present conditions in a single family residence might produce 2.25 lb/cap/day of refuse and 40 gals/cap/day of sewage (of which, say, 35 gals/cap/day is available for grinding under the Foster-Miller concept), then a 50 percent increase in refuse production and a 20 percent decrease in water production would increase minimum grinding consistency from 0.8 to 1.9 percent.

The Trade-off. There is, of course, no technical reason why one cannot grind at high consistency using reusable wastewater; this would solve any problem of inadequate quantity because even at 5 lb/cap/day and 7 percent consistency, only 6 gallons per day are required for grinding. However, there may be strong economic reasons against such an alternative; if so little wastewater is required, then it may be cheaper to use freshwater alone (supplemented by laundry effluent). Note that while using freshwater would increase the sewage input from the home by 12 to 20 percent (6 gallons over 30-50 gallons normal usage), it would increase sewage input to the treatment plant by only 6 percent (6 gallons over 100 gal/cap/day typical of existing treatment plant inflows). Furthermore, an offsetting increase in sewage flow would probably be beneficial for hydraulic transport because the efforts at eliminating infiltration and reducing water consumption in other areas will tend to decrease sewage flows (and hence decrease the flow velocities, leading to increased deposition).

Unfortunately, the economic analaysis of Chapter VI will show both alternatives to be too costly, because the pressurized building connection will also involve capital expenditures of about $450-$500, which is still in excess of the grinding unit itself. The obvious conclusion is that one must seek a grinding option that involves neither the plumbing modification nor the pressurized building connection.

One way of achieving this is to grind at high consistency with recirculation rather than continuous discharge. Discharge to the existing building connection would occur only during periods of high flow from other household devices at which time adequate flow would be present to transport the grinder effluent without difficulty; for example, flushing of toilets and pumping cycles in dishwashers might be used to trigger grinder discharge to the building connection. Because high solids concentrations would be used, the matrix effect would prevent any significant settling even during the several hours of storage that might elapse between the grinding cycle and complete discharge. A determination of whether such a concept is feasible or

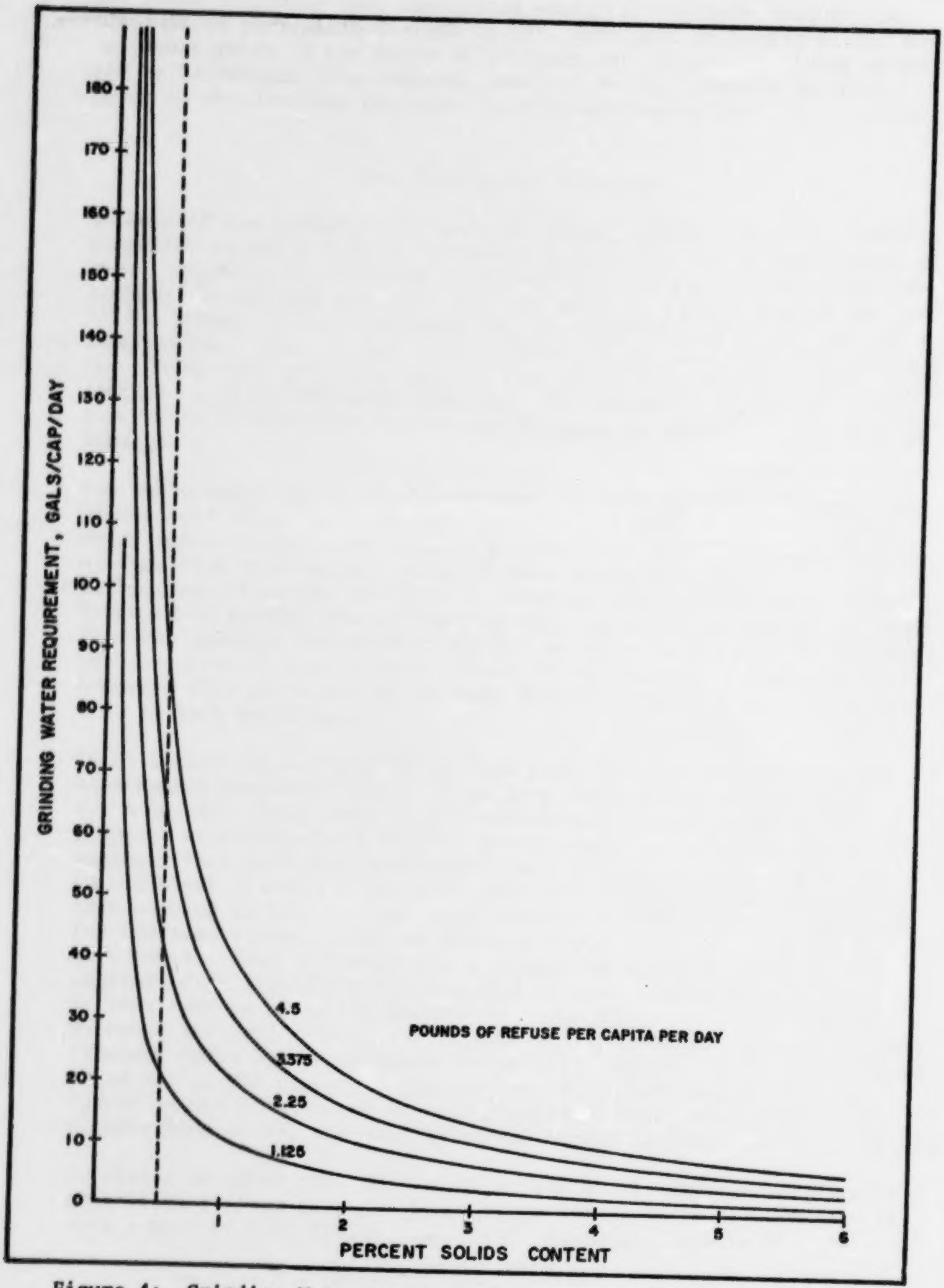


Figure 4: Grinding Water Requirement

not would obviously need additional study; it is clear however that alternative conceptual designs to that developed by Foster-Miller must be investigated if the costs of grinding for individual living units are to be brought to acceptable levels. We shall return to this point in the detailed economic analysis of Chapter VI.

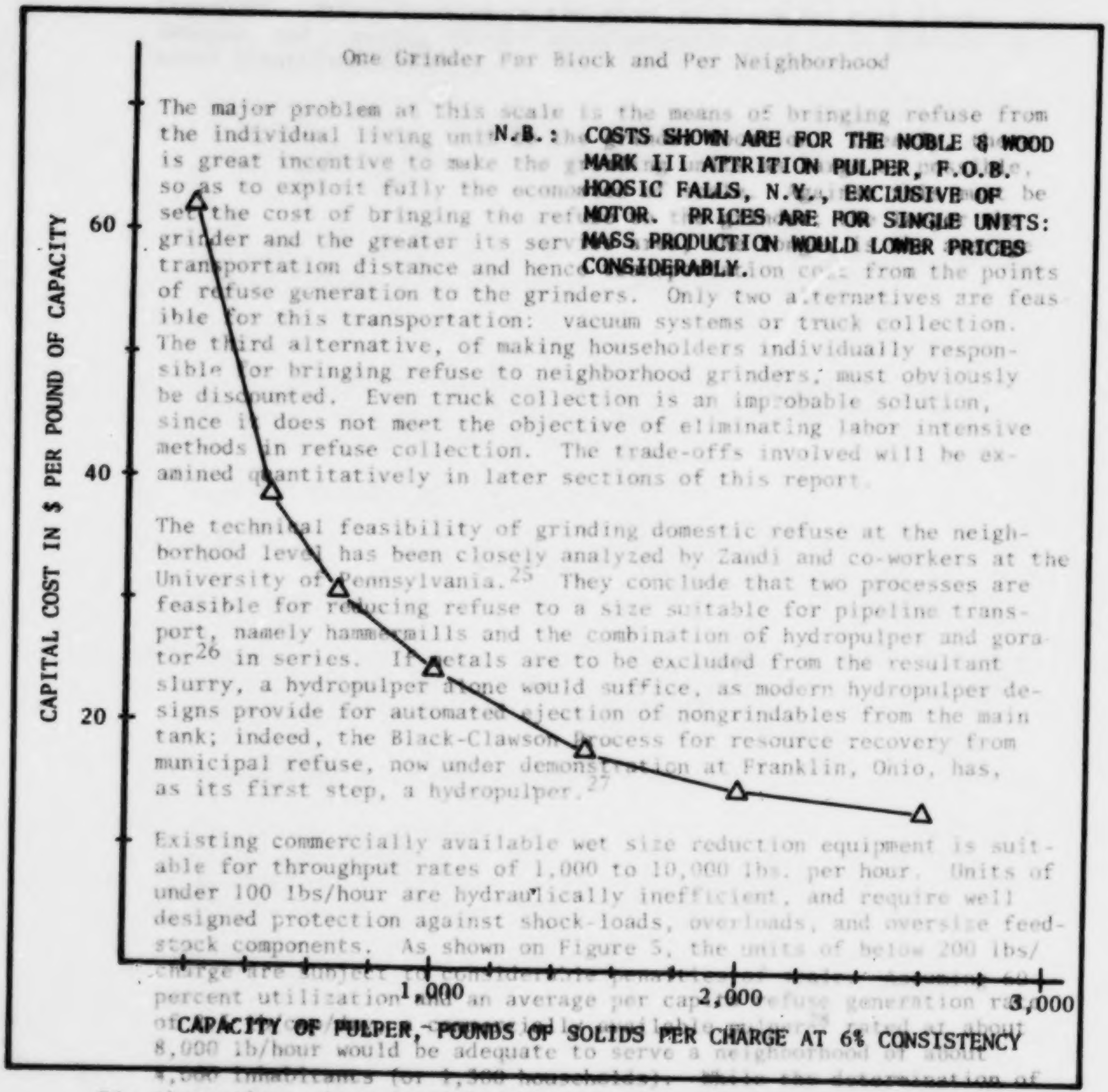
One Grinder Per Structure

Because of the economies of scale in grinder costs, there is a strong incentive to install as few grinders as possible in any one structure. These economies of scale are illustrated on Figure 5, which shows the decrease in average unit cost with increase in total capacity for one of the grinder designs suitable for the neighborhood or one per structure option. Even if costs were linear, it is clear that most designs for living unit grinders, such as that devised by Foster-Miller, would suffice to serve many more than just one household, since the daily production of refuse of one household could be ground in less than 30 minutes.[22]

The one grinder per structure approach is most suitable in structures of vertical extension where gravity chutes could be easily used to bring refuse to basement-located grinders, as in the existing chutes of high-rise structures. A factor that mitigates against the one grinder per structure approach in existing two- to four-story structures where gravity chutes would be very expensive to add is the fact that the domestic convenience benefit would be eliminated if residents were required to convey their refuse to the basement grinder by hand. However, this would not be any more inconvenient than existing practice in such buildings.

Still a more serious problem at this scale is that of ownership and maintenance responsibility. Aside from the problem of vandalism, which in many cases completely overshadows other problems in this respect, experience with on-site incinerators in apartment blocks suggests that deficient maintenance may be a major stumbling block to efficient operation, and many apartment houses now provide living unit washing machines rather than communal basement-located machines for the same reason. Similar problems might arise in condominium structures. Thus, although the economies of scale may reduce total capital costs significantly, the lack of user responsibility makes it very easy to abuse the machine by items which can cause jamming. Although the larger units can be more easily provided with extra power, frequent abuse may drastically reduce user responsibility to the point of rejecting the concept. The problem of adequate supervision of operation and maintenance is much greater at this scale than at the neighborhood scale, and must be solved before implementation is feasible.

It should be noted that the latest estimates of domestic solid waste generation in high-rise dwellings range from 1.25 to 1.75 lbs/cap/day, with a mean of 1.48 lbs/cap/day.[23,24] Although there is much less



N.B.: COSTS SHOWN ARE FOR THE NOBLE & WOOD MARK III ATTRITION PULPER, F.O.B. HOOSIC FALLS, N.Y., EXCLUSIVE OF MOTOR. PRICES ARE FOR SINGLE UNITS: MASS PRODUCTION WOULD LOWER PRICES CONSIDERABLY.

Figure 5: Cost of pulpers as a Function of Capacity (Source: Noble and Wood)

than that for single family homes, wastewater flows may also be less, and thus the question of sufficiency of available recycled grinding water remains even in this type of housing.

One Grinder Per Block and Per Neighborhood

The major problem at this scale is the means of bringing refuse from the individual living unit to the grinder location. Clearly, there is great incentive to make the grinding units as large as possible, so as to exploit fully the economies of scale. Against this must be set the cost of bringing the refuse to the grinder; the larger the grinder and the greater its service area, the longer is the average transportation distance and hence transportation cost from the points of refuse generation to the grinders. Only two alternatives are feasible for this transportation: vacuum systems or truck collection. The third alternative, of making householders individually responsible for bringing refuse to neighborhood grinders, must obviously be discounted. Even truck collection is an improbable solution, since it does not meet the objective of eliminating labor intensive methods in refuse collection. The trade-offs involved will be examined quantitatively in later sections of this report.

The technical feasibility of grinding domestic refuse at the neighborhood level has been closely analyzed by Zandi and co-workers at the University of Pennsylvania.[25] They conclude that two processes are feasible for reducing refuse to a size suitable for pipeline transport, namely hammermills and the combination of hydropulper and gorator[26] in series. If metals are to be excluded from the resultant slurry, a hydropulper alone would suffice, as modern hydropulper designs provide for automated ejection of nongrindables from the main tank; indeed, the Black-Clawson Process for resource recovery from municipal refuse, now under demonstration at Franklin, Ohio, has, as its first step, a hydropulper.[27]

Existing commercially available wet size reduction equipment is suitable for throughput rates of 1,000 to 10,000 lbs. per hour. Units of under 100 lbs/hour are hydraulically inefficient, and require well designed protection against shock-loads, overloads, and oversize feedstock components. As shown on Figure 5, the units of below 200 lbs/charge are subject to considerable penalties of scale. Assuming 60 percent utilization and an average per capita refuse generation rate of 2.5 lb/cap/day, a commercially available pulper[28] rated at about 8,000 lb/hour would be adequate to serve a neighborhood of about 4,600 inhabitants (or 1,300 households). While the determination of the optimum size of neighborhood grinders is one to be answered by the economic analysis, it is nevertheless probable that existing technology could be extended to neighborhood refuse grinding with little difficulty.

Neighborhood grinders must obviously be sited with some care, because the flow in the interceptor receiving the ground refuse must be sufficient to dilute the 8-15 percent solids concentrations of the grinder effluent to less than the 1 percent required for hydraulic transport. Stratification at the point of discharge must clearly be avoided, and a mixing chamber would probably need to be provided to avoid stratified flow.

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3. *Ibid*.

4. See Turner, H. E., and H. E. McCarthy, "A Fundamental Analysis of Slurry Grinding," *A.I.Ch.E. Journal*, July 1966, pp. 784-789, for a discussion of this point.

5. Fisk and Guzdar, *op*. *cit*., p. 32.

6. *Ibid*., p. 82.

7. *Ibid*., pp. 110-112.

8. Nebiker, J. and P. Meier, "Hydraulic Disposal of Solid Wastes," *Proc*. 1st Annual Northeastern Regional Anti-Pollution Conference, University of Rhode Island, Kingston, R. I., July 1968.

9. We shall refer to this alternative as the "Foster-Miller Concept."

10. The higher the viscosity of the system, the more is the mobility of the contained solids reduced, thereby increasing the effect of shear forces produced by equipment components and increasing size reduction effects. See Turner and McCarthy, *op*. *cit*., p. 784.

11. A timing device on the grinder might solve the problem of grinding during low flow periods were stratification encountered.

12. The average washing machine consumption per load according to the September 1972 edition of *Consumer Reports* is approximately 50 gallons. From an article by Anderson and Watson, "Patterns of Household Usage," *Journal AWWA*, October 1967, pp. 1228-1237, the daily usage of automatic washers is 0.7 cycles for about 50 percent of the time while maximum weekly use is ten cycles. Therefore, the volume of washing effluent available per week would be between approximately 200 to 500 gallons per household per week.

13. EPA Contract 68-01-0041, "Demonstration of Waste Flow Reduction from Households."

14. Fisk and Guzdar, *op. cit.*, p. 11.

15. "Data Acquisition and Analysis System, Quarterly Report, January - March 1972," Report by ACT Systems to the EPA Solid Waste Management Office, April 1972 (EPA Contracts 68-03-0034 and 68-03-0097).

16. Cleveland, Ohio; Wichita Falls, Texas; Orlando, Florida; Denver, Colorado; and Buffalo, New York.

17. See for example, Watson, K. S., R. Farrell, and J. S. Anderson, "The Contribution from the Individual Home to the Sewer System," *J. WPCF*, 39, 12, 2039 (December 1967).

18. Carcich, I., L. Hetling, and R. Farrell, " Pressure Sewer Demonstration," EPA Technology Series, Report EPA-R2-72-091, November 1972.

19. *Ibid.*, p. 161.

20. Fisk and Guzdar, *op, cit.*, p. 28. Parenthetically one might note that bath and laundry effluents also contain some fecal matter.

21. The effectiveness of such devices is currently being evaluated by the Electric Boat Division of General Dynamics under EPA Contract 68-01-0041, "Demonstration of Waste Flow Reduction from Households."

22. Some design modifications might be required, but these would not increase costs significantly.

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27. Herbert, W., "Recycling Municipal Waste," *Chemical Engineering,* January 10, 1972.

28. See for example, the Nobel and Wood Mark III Attrition Pulper 66-11-9 rated at 2600 lbs/solids per charge at 6 percent consistency; with a pulping cycle of 20 minutes.

CHAPTER III

HYDRAULIC TRANSPORT

Introduction

The hydraulic transport of ground refuse, preferably, but not necessarily in the existing sanitary sewer system, is the key component of any wet system for refuse collection. Indeed, it is the fact that sewage solids carried by existing gravity sewer systems are only a very small fraction of the total solids carrying capacity that makes the sanitary sewer system so potentially attractive as a means of hydraulic conveyance to eliminate conventional refuse collection.

In the absence of actual experience, there are several paths that can be pursued to examine the feasibility of hydraulic transport in existing sewer systems. A critical examination of the problems of solids deposition under existing conditions is the obvious initial step. The solids loads in systems where many garbage grinders are present are much higher than where they are not present, and the experience of such systems may prove helpful in identifying potential problems. Finally, there are some experimental studies that have investigated the feasibility of transporting ground refuse in gravity sewers. These studies indicate that hydraulic transport in sewers is indeed feasibly under controlled experimental conditions, but there is to date no experience in real sewers of 6- and 8-inch diameter that constitute the bulk of a total system.

Deposition Characteristics and Critical Velocity Requirements in Existing Systems

Deposition Problems in Street Sewers. Raths and McCauley[1] conducted an experimental program in which sand of various particle sizes was deposited in an 80-ft. section of new 8-inch clay pipe to determine deposition characteristics. They chose sand for the deposition study since it is easily graded and of nearly uniform specific gravity and "since sand has the highest specific gravity commonly found in sanitary sewers."[2]

The factors affecting deposition were listed as:

1. Type, size and specific gravity of material
2. Quantity of flow
3. Depth of flow
4. Velocity of flow
5. Pipe slope
6. Pipe alignment
7. Pipe size
8. Pipe joints

9. Pipe age
10. Pipe roughness coefficient
11. Sewer construction practice

They concluded that:

1. Deposition was definitely influenced by pipe slope, particle size, and depth of flow. The effects of the other aforementioned factors were not directly measured.
2. Solids suspended in the sewage apparently had little effect on deposition.
3. The principal influence in initiating deposition is pipe joints.
4. The minimum pipe grade, while important, is a secondary consideration relative to joints and proper construction techniques.[3]

Raths and McCauley developed the following expression for the depth of flow d/D required to prevent deposition in an 8-inch pipe:

$$\frac{d}{D} = (-0.63 \log S - 0.05)\ P^{0.333} \qquad [1]$$

where S is the slope in percent and P the largest particle size in millimeters (mm) which will not deposit, assuming a specific gravity of 2.7. Thus for a half-full 8-inch pipe at a slope of .4 percent (minimum recommended by design manuals for two fps scouring velocity), the largest particle size of sand which will not deposit is approximately 15 millimeters or 1/2-inch. Because the glass particles emanating from the grinder would have the same specific gravity and the same angular shape as sand, similar deposition characteristics can be expected, and because the size of glass particles from a household grinder is not expected to exceed 0.25 inches, it appears that new 8-inch clay sewer pipe flowing half full should accept ground glass. However, if the depth of flow drops to two tenths of full depth for extended periods of time, as might be expected in the upper laterals of a collection system, the maximum particle size allowable would be in the order of 1 mm. In all likelihood, not all ground glass particles emerging from the grinder will be this small, and therefore, some deposition may indeed be expected during periods of low flow.

It is evident from Raths and McCauley's data that if the recommended velocity of 2 fps were used as the major criterion, deposition and blockage should have resulted for most of the particle sizes investigated. Since this is not the case, they conclude that "this 'rule of thumb' which relies on velocity, is only an approximation of the combined effect of velocity and depth of flow."[4] In effect then, they are saying that sewers are overdesigned and much shallower slopes and lower velocities are sufficient.

Not all investigators are as optimistic as Raths and McCauley on the scouring abilities of sewers. Pomeroy[5] reports that "low velocity is both a cause and a result of fouling of the sewer." His research was undertaken to find out more about the actual hydraulic conditions existing in small sewers and has significant relevance to this project. The results of hydraulic tests in 95 sewers are presented and the factors influencing the hydraulic conditions are discussed. Examination of the data revealed that many sewer lines, especially in flat terrain areas such as Texas and Florida, were not laid at sufficient slope to produce the recommended 2 feet per second (fps) scouring velocity. No direct reference was made as to the excessive fouling of these specific sewers, but the author concluded that the data obtained provided incidental support for the accepted view that a velocity of 1.6 to 2 fps is needed to avoid excessive accumulations of debris. Observations revealed that significant fouling occurs in some lines even under these flow conditions. Cleaning is often required if the sewer is to retain good hydraulic properties.

Since a velocity of 2 fps in a 6-inch pipe is reached only when the flow is about .35 cubic feet per second (cfs), it was Pomeroy's opinion that a slope as low as .4 percent should not be used for a sewer lateral designed to serve less than the equivalent of 200 homes. This is obviously not the case in many residential subdivisions.

Pomeroy also concluded, as did Raths and McCauley, that poor construction, including irregularities in slope, is often a cause of poor hydraulic conveyance. Of all the sewers tested, asbestos cement sewers showed better hydraulic coefficients than the vitrified clay sewers, with the concrete sewers being the poorest.

Wicks[6] provides a graphic description of the nature of solid particle motion in horizontal pipes. He explained that the significant forces acting on solid particles include gravity, buoyancy, lift and drag. The first two forces are constant, while the latter two vary with flow conditions. The particle shape and the roughness of surface also have an effect. Rounded particles roll, especially if the boundary surface is smooth. Long, thin particles tend to slide if the surface is smooth or may tumble if it is rough. Rough or jagged particles move in a succession of jumps or bounces often called "saltation flow."

The most comprehensive articles on minimum velocity requirements for transport of sanitary sewage is presented by McPherson, Tucker and Hobbs[7] for the ASCE Combined Sewer Separation Project. Because insufficient information existed on minimum transport velocities for full pipe flow, tests were conducted at the Central Engineering Laboratories of the FMC Corporation in Santa Clara, California, using 2-inch through 8-inch horizontal clear plastic pipe. The results of these tests, together with those of Ambrose and Craven, are shown in Figure 6 as a function of concentrations of sand in sewage. If all the glass in residential refuse were ground, one might expect a glass concentration in the sewer as shown on Figure 7. Average glass concentrations might thus range from 540 parts per million (ppm) in small laterals carrying 30-gal/cap/day to 160 ppm in larger sewers carrying 100-gal/cap/day. Comparison with Figure 6 indicates that these concentrations might cause problems in existing sewers that rarely reached maximum velocity.

Deposition Problems in Building Connections. The preceding discussions on deposition characteristics and critical velocity requirements of sewers mainly concern street sewers from 6 inches in diameter to the largest interceptors. Indeed, most of the technical literature deals with only this portion of the sewer transport network. However, even though building connections are theoretically subject to the same critical velocity requirements, the much smaller diameter and the extreme fluctuations in flows and solids loads may result in some special problems.

A comprehensive report on this aspect of the problem was prepared by the Building Research Advisory Board (BRAB).[8] It was determined that foreign objects deposited in the sanitary sewerage system are a major cause of stoppages in house sewers. More often than not, these stoppages could have been avoided by proper installation. Faulty installation may result from poor workmanship, or a lack of knowledge of the proper installation method for the particular pipe or jointing materials or soil condition.

Building sewers are also exposed to highly unsteady flow conditions. Flowrates can vary from zero during periods of inactivity to the high flowrate following the flushing of a toilet. The higher flowrates are required to effectively transport the solid matter to the street sewer. Cosens and Hannemann[9] found that the average discharge of a water closet (23 gpm) would produce sufficient flow to move a layer of deposited eggshell down the pipe where it would remain until another increase in flow occurred.

The Impact of Garbage Grinders

As noted previously, the introduction of refuse into sewers is not without precedent. In the late 1940's, garbage grinders were attracting considerable attention, although they were viewed with disfavor by many municipalities fearing that such practices would unduly increase the burden on the sewage collection and disposal facilities. Cosens and Hannemann[10] stated in 1949 that:

> One important question concerns the ability of sewers to transport the heavy ground-garbage solids if present sewer design standards were followed. It was felt that we could not be sure whether sewers laid on minimum recommended grades and having limited flows would transport the heavy solids found in domestic garbage.

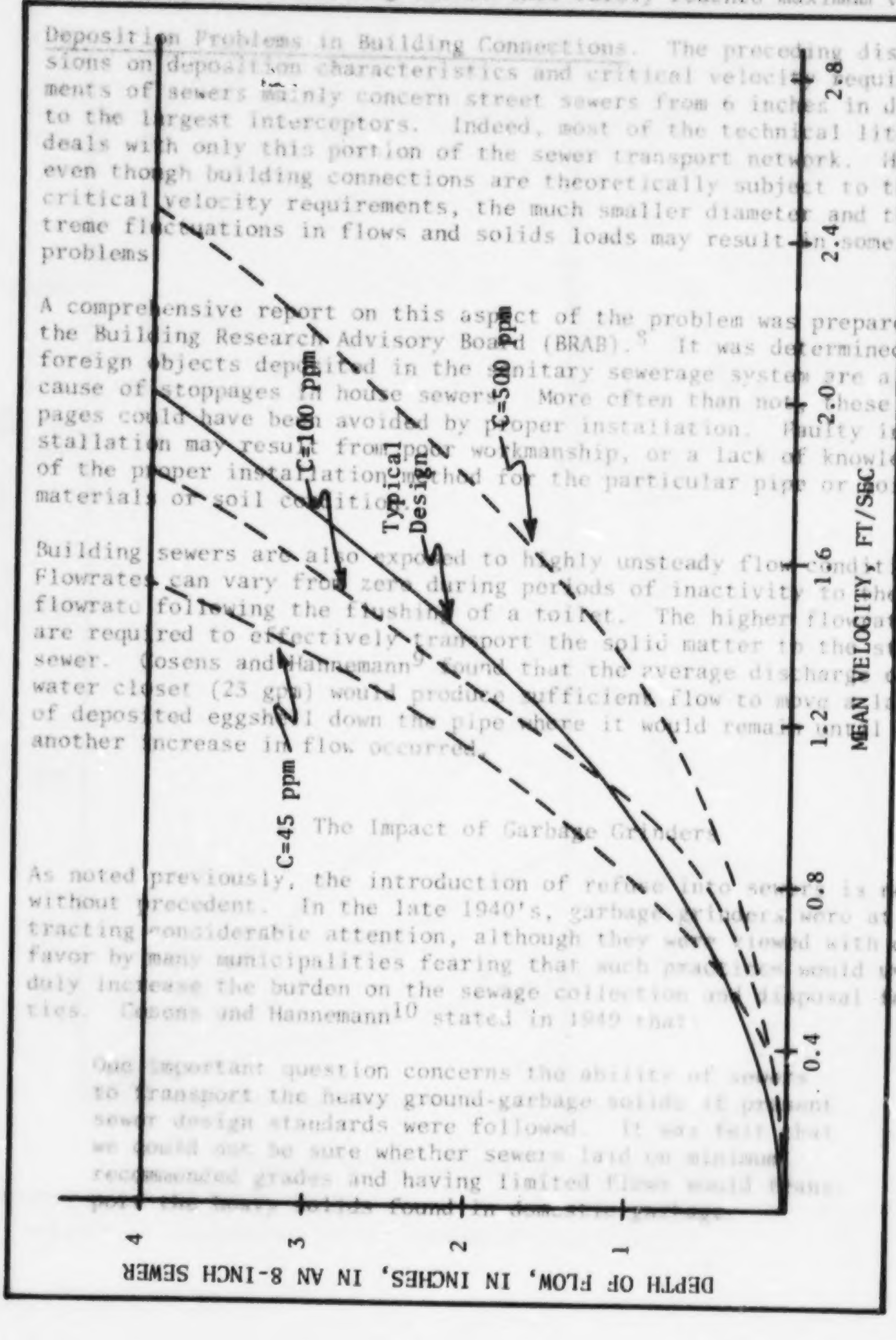

Figure 6: Minimum Transport Velocities for Glass in an 8-inch Gravity Sewer (Source: McPherson, *et al.*, *op. cit.*, page 13).

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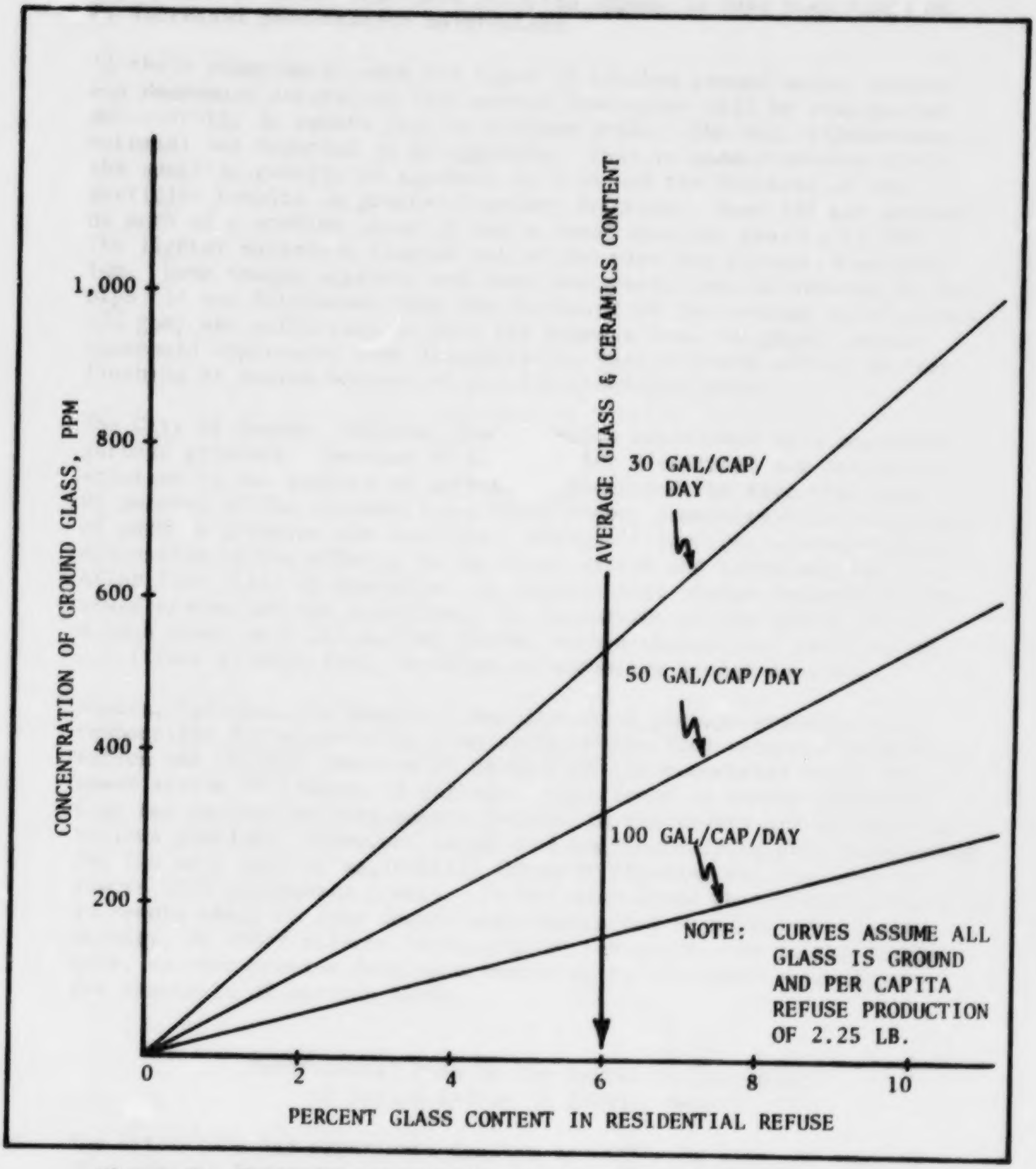

Figure 7: Concentration of Ground Glass in Sewers

However, some twenty years of experience with garbage grinders have revealed no insurmountable problems in the collection system. The municipalities that do ban garbage grinders have done so because of the inadequate capacity of their treatment plants,[11] and most of the deposition problems that have occurred appear to have been resolved by increased preventative maintenance.

In their experiments with all types of kitchen ground waste, Cosens and Hannemann determined that ground food waste will be transported successfully in sewers laid at minimum grade. The most troublesome material was reported to be eggshell. This is understandable since the specific gravity of eggshell is 2.30 and the flatness of the particles results in greater boundary friction. Bone did not present as much of a problem since it has a lower specific gravity (2.08). The lighter materials floated out of the pipe and presented no problem. Even though eggshell and some bone particles did deposit in the pipe, it was determined that the discharge of the average water closet (23 gpm) was sufficient to move the deposit down the pipe. Other household appliances were discounted as having little effect on the flushing of solids because of the low discharge rates.

The City of Jasper, Indiana, has extensive experience with household garbage grinders. Because of the need for a suitable and economical solution to the problem of garbage disposal and the fact that over 92 percent of the residents own their homes, community-wide installation of garbage grinders was feasible. Wraight[12] provides a comprehensive discussion of the effects on the sewer system and treatment facility. After five years of operation, he reports that sludge deposits in the sewer system are not a problem. An inspection of the outlet of an 8-inch sewer on a .61 percent grade, with a theoretical velocity of 2.5 ft/sec flowing full, revealed no excessive sludge deposits.

Aurora, Colorado, is another community where garbage grinders are responsible for disposal of a majority of the food wastes. In 1961, Watson and Clark[13] reported 58 percent of its households using the sewer system to dispose of garbage. Experience in Aurora indicates that the garbage grinder wastes carried in the sewers are creating no serious problems. However, because of the increase in grit (consisting for the most part of eggshells), frequent flushing was required in sewers with inadequate grades. It was also noted that clogging occurred in sewers which to some degree were obstructed by roots, pieces of masonry, or other objects introduced by the users. As in the Jasper case, an odor problem developed requiring fairly heavy expenditures for chemicals of various kinds.

Experimental Data on the Hydraulic Transport of Ground Refuse in Gravity Sewers

The literature and experience dealing specifically with the ability of sewers to transport solid waste is extremely limited. In fact, only three studies can be considered of any consequence to our analysis. One was a result of depositing very coarsely ground refuse in large sanitary sewers performed in 1963 by the County Sanitation Districts of Los Angeles County.[14] The other two are studies conducted by Foster-Miller Associates for the Environmental Protection Agency.[15,16]

The Los Angeles Experiments. In 1963 and 1964, the Los Angeles County Sanitation District conducted some tests on the feasibility of transporting ground refuse in large diameter interceptors.[17] On two separate occasions, unwetted ground refuse was dumped into a manhole structure on a 78-inch diameter sewer line flowing nearly full with a velocity between 5 and 6 fps. It should be noted that such velocities are rarely encountered in the more widespread smaller diameter sewers, and the results of this study cannot therefore be generalized. The sewer transport route was 13 miles long and included six inverted siphons of varying length. The first loading consisted of 7.25 tons of very coarsely ground refuse of which many pieces were up to 3 and 4 inches in diameter. Glass and metal were removed prior to grinding. The ground material was introduced into the sewer over a period of one-half hour, or at the rate of approximately 15 tons per hour. The second loading consisted of the same material at 2-inch maximum size. As in the first test, glass and metals were excluded.

In both cases, visual observations indicated no stoppages due to refuse loading and only a trace of the refuse was visible as floating material. The 13-mile trip was accomplished in approximately five hours, indicating an average travel rate for the solid materials of slightly less than 4 ft/sec. There was no evidence to indicate that combustible refuse could not be successfully transported in a sewer system, although it was not possible to determine from these two loading tests the solids carrying capacity of the sewer involved. The researchers felt that the utilization of the sewer for transporting refuse on a continuous basis would require the removal of grit and other heavy materials prior to introduction of the remaining portion to the sewer.

However, hydraulic conditions in a large sewer flowing full are quite different from the conditions in the 6- and 8-inch lines common in suburban areas. Here the velocity at full flow may be only 2 fps and the occasions when the pipe is flowing full are rare. Yet it is in such small diameter sewers where over 90 percent of all stoppages occur.

Transport through Straight Pipes. A first series of laboratory experiments conducted by Foster-Miller in 1971 for the EPA Solid Waste Program were designed to establish the feasibility of hydraulic transport of ground refuse in straight sections of sewers, with interest centered on head loss and velocity determinations.[18] The tests were conducted to measure the effects of pipe roughness, refuse type, refuse concentration and flowrate in glass, transite and corrugated aluminum sewer pipes. All pipes were 6 inches in diameter. Pretreatment of the refuse involved a grinding operation of which many types were tested, and the grinding operations were all designed to produce particle sizes smaller than 1.5 inches. A particle of 1.5 inches was determined to be the maximum transportable. As a result, the size and shape of the particles used in the sewer transport test included paper and plastic pieces of less than 1.5 inches, glass and metal pieces less than .5 inches in diameter, and cloth and rag strips up to 6 inches in length.

The test facility, as designed, did not allow a study of the continuous flow of the heavy constituents of refuse such as glass and metals. Separate scouring velocity tests were conducted to determine the minimum flow velocity required to scour a layer of the heavier materials likely to be deposited in the bottom of the pipe. These scouring tests were conducted in the glass pipe only and involved the placement of ground glass and metal fragments in the test pipe section. Scouring of these deposits by the flow of refuse slurry was observed as a function of velocity in order to establish the minimum scour velocity. Use of the glass pipe allowed observations of flow of different constituents of ground refuse. Cloth and rags which were usually ground into long, stringy pieces were the source of most of the major problems. The cloth pieces had a tendency to wrap themselves around any obstructions placed in the flow path. Investigators at Foster-Miller felt that unless cloth and rags can be cut into small rectangular pieces, they should be eliminated from the flow.

Foster-Miller determined that the minimum scour velocity for ground glass and metal deposits was 2.5 ft/sec, and a summary of the scour velocity tests is shown on Table 4. Although many existing sewers are designed to provide this velocity, the WPCF Manual of Practice for the design of sanitary and storm sewers[19] notes that a 2-ft/sec minimum velocity requirement is quite common.

The effect of refuse concentration on the hydraulic flow regime and the scouring velocities was summarized by Foster-Miller as follows:[20]

> At dilute refuse concentrations of less than 1.5 percent and flow velocities greater than 1.5 ft/sec, the refuse slurry flows as a heterogeneous suspension without settling of the light refuse constituents. At these dilute concentrations, but at very low velocities of less than 0.8 ft/sec, the regime changes to a sliding bed type of flow where the particles form a bed which slides along the bottom of the pipe. At these low velocities, the possibility of an obstruction in the flow path causing solids buildup is high. At high refuse concentrations of greater than 2 percent and velocities up to 4 ft/sec, a plug type flow occurs. All the solids move en masse without relative motion. The suspension at these concentrations is essentially nonsettling. Even heavy glass and metal pieces can be carried in suspension at these concentrations.

Table 4: Results of Scour Velocity Tests

Material	Slurry Concentration, Percent	Pipe Gradient, ft./ft.	Depth of Flow, Inches	Scour Velocity, ft./sec.	Average Scour Velocity, ft./sec.
Hammermill ground glass and metal	0.0	0.002	2	2	2.5
	0.5	0.002	5	2.5	
	0.0	0.004	2.5	2.5	
	0.0	0.006	1.75	2.5	
	0.0	0.008	1.5	2.8	
	0.5	0.01	2	2.5	
	1.0	0.01	1.75	2.5	
steel cylinders	0.0	0.002	2	2	2.5
	0.0	0.004	2.5	2.5	
	1.0	0.008	1.75	2.5	
3/4-x 3/4-inch square pieces of steel can stock	0.0	0.002	2	2.0	2.5
	0.5	0.002	5.5	1.8	
	0.0	0.004	2.5	2.5	
	0.5	0.004	2.75	2.5	
	0.0	0.008	1.75	2.5	
Mixed pieces	0.0	0.004	6.0	3.0	3.1
	0.0	0.006	5.5	3.3	
	0.0	0.008	3.5	3.0	
1/16-inch thick Rectangular pieces 1/4-to 1/2-inch size	0.0	0.004	6	2.5	2.9
	0.25	0.006	1.75	3	
	1.0	0.002	2.25	3.2	

Source: Guzdar and Rhee, op. cit., p. 83

> At the dilute concentrations of less than 1.5 percent, the heavy components of refuse, namely glass and metal, settle to the bottom. A minimum velocity of 2.5 ft/sec is required to scour these deposits and maintain self-cleaning conditions in the pipes. With plug flow at the higher concentrations of greater than 2.0 percent, the heavy particles are retained in the fibrous suspension and move en masse with the slurry. No minimum velocity is required.

They also concluded that the limiting refuse concentration above which the head losses exceed significantly that of sewage alone, varies with the smoothness of the pipe and the depth of flow. These concentrations are higher for smooth pipes and greater flow depths. For example, if a smooth pipe is flowing at 30 percent of its full depth, the limiting refuse concentration is .5 percent, whereas at 80.0 percent full depth, it can be as high as 1.5 percent.

Transport through Sewer Appurtenances. A second study conducted by Foster-Miller for EPA in 1972 was designed to experimentally investigate the gravity flow of ground household refuse through a wide range of sewer appurtenances.[21] The hydraulic gravity transport of a ground refuse slurry through sewer appurtenances was investigated in an experimental test loop. Tests were run using 22-1/2°, 45°, and 60° inverted siphons; a running trap; 45°, 60° and 90° horizontal bends; straight, size transition and 90° bend manhole configurations; a tee junction; a typical pump inlet design; and several obstacles typical of sewage flow situations.

The investigations indicated that the hydraulic transport of ground refuse at concentrations up to 1.0 percent was feasible. At very low velocities small head losses were found to occur at specific appurtenances, but these were not considered significant relative to the total head available. At flow velocities of 2.5 feet per second and above, these head losses become negligible.

At refuse concentrations on the order of 0.5 percent, head losses in the appurtenances were frequently reduced from the clear water case, indicating improved flow characteristics at these low concentrations. This was in agreement with the results obtained in the previous study for straight pipe flow. At a refuse concentration of 1.5 percent, however, significant increases in pressure drop were noted for most of the appurtenances tested.[22]

At the third elbow of inverted siphons heavy solids were found to accumulate unless velocities considerably higher than the 2.5 feet per second design minimum were present to aid in scouring. However, these accumulations did not appear to present a critical problem since they reached a steady-state height before any possibility of blockage occurred. Scouring in the siphon flowing full was aided by the increase in local velocity due to the restricted flow area at the deposition.

As the deposition grew, the local velocity increased until the required scouring velocity was reached.[23]

Flow in pump inlets was not found to be hampered by the addition of ground refuse in the concentrations tested. Even heavy solids did not plug the wet well and pump inlet when tested at concentrations of 3.0 percent. The flow around obstacles, sluice gates, dams and overflow weirs was not affected significantly by the addition of refuse at concentrations up to 1.5 percent. Heavy solids continued to accumulate upstream of dams and overflow weirs but only until steady-state was reached at which solids were added and scoured at the same rate.[24]

In manholes, the solids accumulation occurred not within the manhole but immediately downstream of the outlet where the slope of the pipe is suddenly increased. The flow velocity decayed in a hydraulic jump and the heavy solids settled in the pipe. In steady-state, the depositions extended downstream until the flow velocity naturally reached the velocity required to scour the particles in a straight pipe. It was concluded that in steady-state, a long flat pile of heavy solids would be expected just beyond the manhole outlet.[25]

At junctions a number of transient deposition effects were observed.[26] In general, the effect of the flow entering the main stream through a lateral is to locally reduce the velocity of the main stream and thus encourage deposition of the heavy solids just upstream of the junction. Increased velocities were required in the main during periods of appreciable flows from the lateral to insure that the heavy solids would carry through the junction. Under these conditions, a velocity of approximately 4.5 feet per second was required upstream of the junction to carry the heavy solids through the junction and downstream. This velocity was independent of the refuse concentration in the flow. However, once the flow through the lateral ceased, any accumulated solids were quickly scoured by velocities of 2.5 ft/sec, and therefore, whenever the lateral flows are intermittent, no problems should be encountered even if the 4.5 ft/sec scouring velocities are not reached during times of discharge. This would obviously be the case at building connections, and would indicate that grinding might indeed be feasible at high solids concentrations (see Chapter II) with the effluent pumped through the building connection. Any deposition or stratification would be easily eliminated as soon as normal scouring velocities were present once pumping ceased.

In summary, the results indicate that hydraulic transport is feasible if refuse concentrations are below 1.0 percent by weight, a limit that is well above average refuse concentrations likely to be encountered in practice. Foster-Miller concluded that flushing and preventative maintenance would be adequate to solve any deposition problems that did occur, but that ferrous metals should be excluded from the sewer system. However, it should be noted that the conclusion of feasibility is based on the observations under controlled laboratory conditions.

Test demonstrations in real sewers or sewer systems, and laboratory experiments that better simulate the unsteady conditions of reality must be undertaken before any final conclusions are reached.

Alternatives to the Transport of Ground Refuse in Existing Sewer Systems

Briquette Flow Systems. Briquette flow for refuse transport was an idea explored by the Stanford Research Institute.[27] Briquette flow requires that refuse be compressed into 0.5 to 2-inch diameter briquettes, forming a granular slurry with particles of uniform size and specific gravity. An advantage of this uniformity is that the flow of such slurries is very amenable to theoretical calculations, and the granular form of the refuse makes it easy to store and convenient to handle. An especially attractive feature of such a system would be the ease with which briquettes could be separate from the transport medium at the treatment or disposal site. However, if the briquettes tend to break apart in water, they must be sealed prior to mixing with water. This may require large quantities of sealant because of the relatively large surface-to-mass ratio of the refuse briquettes. In their investigation of the theory of pressurized briquette flow, the Stanford Research Institute (SRI) uncovered some serious limitations, including very restrictive operating conditions because the minimum water velocity that will keep briquettes in suspension is very closely related to briquette density. SRI considered the briquette system as one of the least likely candidates for pressure pipeline transport of refuse, and this study finds no evidence that the idea might be more promising for a refuse collection system. Moreover, suitable briquetting equipment is not feasible on a scale less than neighborhood size. Discharge of briquettes into a gravity sewer system would undoubtedly aggravate the problems of blockage at even normal obstructions of the sewer system, and because the question of whether or not sealants would be required has yet to be answered, briquetting is not pursued further in this report.

Slug Flow Systems. Slug or capsule pipelining is another novel method of solid waste transport recently studied by the Stanford Research Institute.[28] This technique involves the formation of refuse slugs by compression, resulting in a series of solid cylinders slightly smaller in diameter than the inside of the pipe, several pipe diameters long, and having about the same density as water. These slugs are then injected into a pressurized pipeline where water, also under pressure from a pump, fills the space around and between slugs, lubricating and propelling them down the pipe. At the disposal site, a screen separates the slugs from the water.

The usefulness of this concept for refuse collection is remote, as a pressure pipeline network in a residential area would be much too intricate to handle a flow of solid waste slugs without stoppages. The behavior of such slugs in a branched network of varying diameter is as yet unexamined, slug flow having been investigated experimentally by SRI only for a single source to sink link of constant diameter and without sharp bends. Injection of such slugs into existing interceptors at neighborhood centers is obviously not a feasible option, because pressurization is required to propel the slugs to their destination. Gravity interceptors would also become hopelessly clogged if the slugs were of sufficiently low density to float.

There is also a critical lack of technical information on the design, operation and capabilities of such a system. Without the background of such experience, the formulation of representative economic cost functions is impossible. As a result, the slug flow concept will not be considered further in this study.

Pressure Sewer Systems. There has been considerable recent interest in pressure sewers, resulting in several EPA demonstration studies in residential areas. However, the results of these studies suggest that some serious problems have yet to be overcome, and it seems unlikely that pressure sewer systems would resolve the problems to be encountered with ground refuse in gravity systems.

Carrich, Hetling and Farrell,[29] reporting on an EPA pressure sewer demonstration system in a suburb of Albany, New York, concluded that the hydraulic design of such systems is critical, and that oversizing of pressure mains leads to serious problems of grease accumulation. Moreover, minimum scouring velocities were found to be much higher than anticipated. The project manager of another EPA demonstration system at Grandview Lake, Indiana,[30] concluded that excessive maintenance required to solve problems of grease accumulations and floating solids made the feasibility of such systems questionable.

The reasons for these problems are not difficult to find. As noted by Waller,[31] the flow velocities in pressure sewers are more sensitive to flow variations than in gravity sewers, as illustrated on Figure 8. If a gravity (open channel) sewer is designed to carry peak flow at 50 percent of full depth, then an actual flow that is only 10 percent of the design peak flow ($q/Q=0.1$) will result in a velocity decrease of only 20 percent. But the velocity in a pressure sewer will decrease 90 percent under the same ratio of actual to design peak flow. Consequently, deposition of ground refuse in a pressure sewer subject to wide flow variations may be more serious than in an open channel sewer. The advantages of the pressure sewer are that much higher and therefore efficient flushing velocities can be achieved, and that the amount of water required for flushing is less.

Extension of the ASCE Pressure Sewer Concept. The use of pressurized conduits has been investigated intensively by the American Society of Civil Engineers (ASCE) as an alternative method of separating combined sewers. As conceived by Professor Gordon M. Fair of Harvard University, separation of sanitary sewage from stormwaters could be achieved by inserting small diameter pipes carrying only sanitary sewage into the much larger existing combined sewers. The one-time

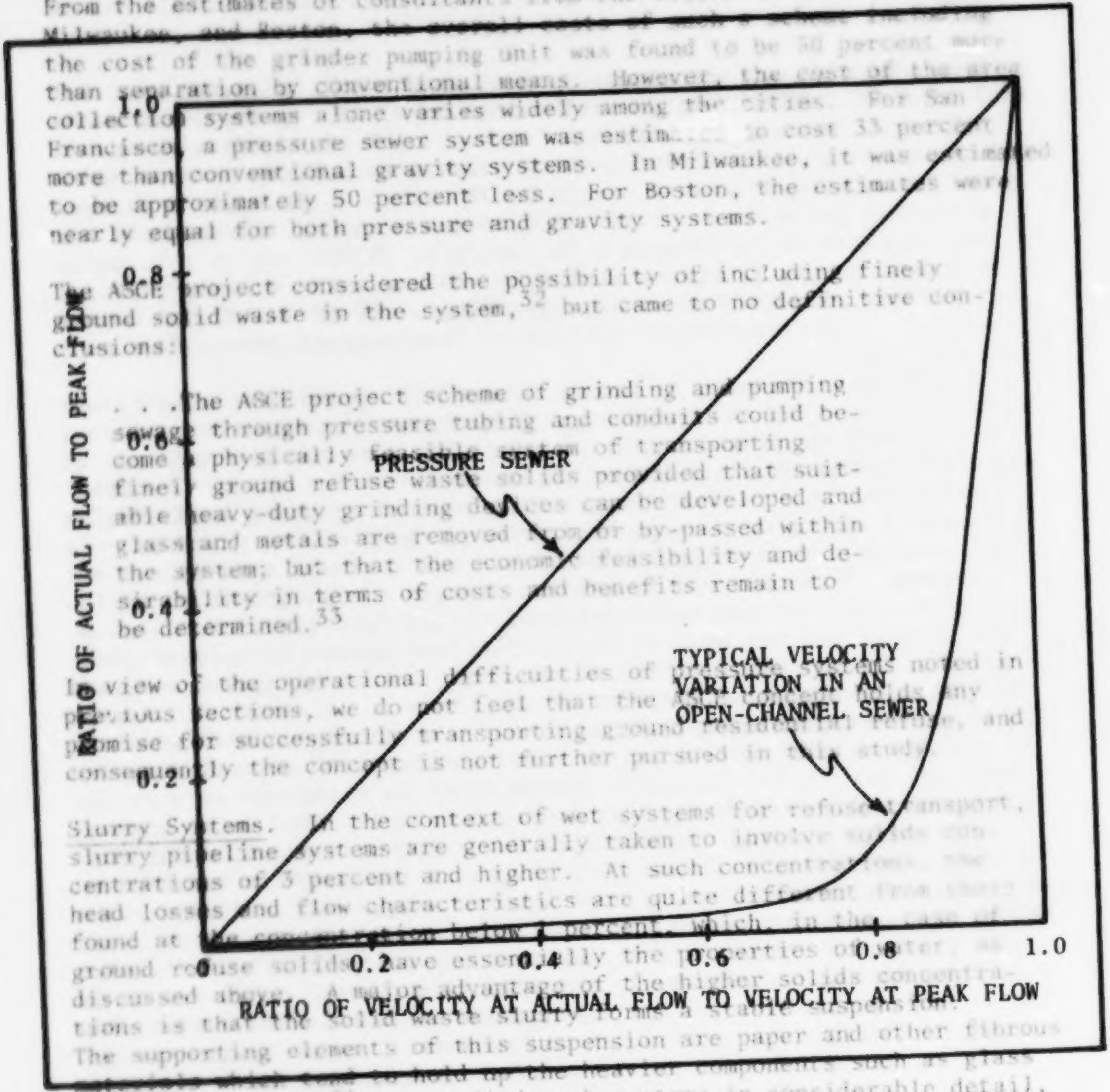

Figure 8: Velocity Variations in Pressure and Open-Channel Sewers (Adapted from: Waller, op. cit., Figure 11).

combined sewers would be retained as conveyors of stormwater while the newly incorporated small diameter pipes would convey the wastewater fraction under pressure to existing interceptors. Each household would contain a grinder-pump-storage unit which would process the sewage and pump it into the new small diameter pipe networks.

From the estimates of consultants from the cities of San Francisco, Milwaukee, and Boston, the overall costs of such a scheme including the cost of the grinder pumping unit was found to be 50 percent more than separation by conventional means. However, the cost of the area collection systems alone varies widely among the cities. For San Francisco, a pressure sewer system was estimated to cost 33 percent more than conventional gravity systems. In Milwaukee, it was estimated to be approximately 50 percent less. For Boston, the estimates were nearly equal for both pressure and gravity systems.

The ASCE project considered the possibility of including finely ground solid waste in the system,[32] but came to no definitive conclusions:

> . . .The ASCE project scheme of grinding and pumping sewage through pressure tubing and conduits could become a physically feasible system of transporting finely ground refuse waste solids provided that suitable heavy-duty grinding devices can be developed and glass and metals are removed from or by-passed within the system; but that the economic feasibility and desirability in terms of costs and benefits remain to be determined.[33]

In view of the operational difficulties of pressure systems noted in previous sections, we do not feel that the ASCE concept holds any promise for successfully transporting ground residential refuse, and consequently the concept is not further pursued in this study.

Slurry Systems. In the context of wet systems for refuse transport, slurry pipeline systems are generally taken to involve solids concentrations of 3 percent and higher. At such concentrations, the head losses and flow characteristics are quite different from those found at the concentration below 1 percent, which, in the case of ground refuse solids, have essentially the properties of water, as discussed above. A major advantage of the higher solids concentrations is that the solid waste slurry forms a stable suspension. The supporting elements of this suspension are paper and other fibrous materials which tend to hold up the heavier components such as glass and metals. Zandi[34] has studied such systems in considerable detail, and concludes on the basis of experiment that the head losses associated with a particular refuse slurry are essentially the same as for a slurry having the equivalent paper concentration. Thus a slurry of 10 percent solid waste which contains 55 percent paper produces pressure losses very similar to a slurry of 5.5 percent paper alone.

This observation forms the basis for Zandi's method of predicting pressure losses. Zandi concluded further that critical velocity requirements are not of overriding importance to the design of a solid waste slurry pipeline. This conclusion is based on the ability of the paper matrix to maintain the heavier particles in suspension even at low velocities. Observations during the experiments revealed that restart of the line after a 24-hour shutdown was no problem.

The head losses at these high concentrations are considerable, as shown on Figure 9. At 10 percent refuse concentration, the head loss is approximately 0.20 ft/ft, which is considerably above that of water alone. Relying on gravity to overcome these head losses would require a slope of 20 ft/100 ft of pipe. Even at 6 percent solids, the head loss is in the order of 0.06 ft/ft, which would require a slope of 6 ft per 100 ft of pipe. As a result, it is evident that existing gravity sewer systems of normal design slopes of approximately 0.6 ft/100 ft for 6-inch pipes would be unusable, and therefore such slurry systems must invariably be pressurized.

Slurry pipelines appear to be most suited to point-to-point transportation of refuse,[35] and have been proposed for this application by the Stanford Research Institute.[36] In a related application, Zandi's[37] "pneumo-slurry" concept for solid waste management involves neighborhood grinders feeding slurry pipelines, with vacuum collection to bring refuse from the points of generation to the grinders. His system also involves the use of the pipeline as a treatment facility to stabilize the organic portion of the refuse.[38] However, because relatively high solids concentrations are involved, only a small portion of sewage available could be used for the slurry, and thus the sewage treatment plant, as it exists today, would still be needed. Conversely, it would not be rational to construct a slurry pipeline from neighborhood grinders to the sewage treatment plant if existing gravity interceptors could do the job as well as appears is the case on the basis of experimental evidence. Also, for the same reasons as we have rejected pressure systems of low solids concentration for collection purposes, we would reject slurry systems; the operational difficulties in a hydraulic pressure system with multiple entry points do not appear to have been satisfactorily resolved. Therefore, we do not see slurry pipelines as a component of the integrated refuse-sewage collection and treatment system herein proposed. This of course by no means invalidates the pneumo-slurry concept as a viable method of solid waste management, and we shall regard the pneumo-slurry concept as an alternative to the entire wet system concept rather than as a component of it.

Physical, Chemical and Biological Effects During Hydraulic Transport

Attrition Phenomena. The process of continual mixing to be expected in the sewer system is not unlike some of the mild pulping processes

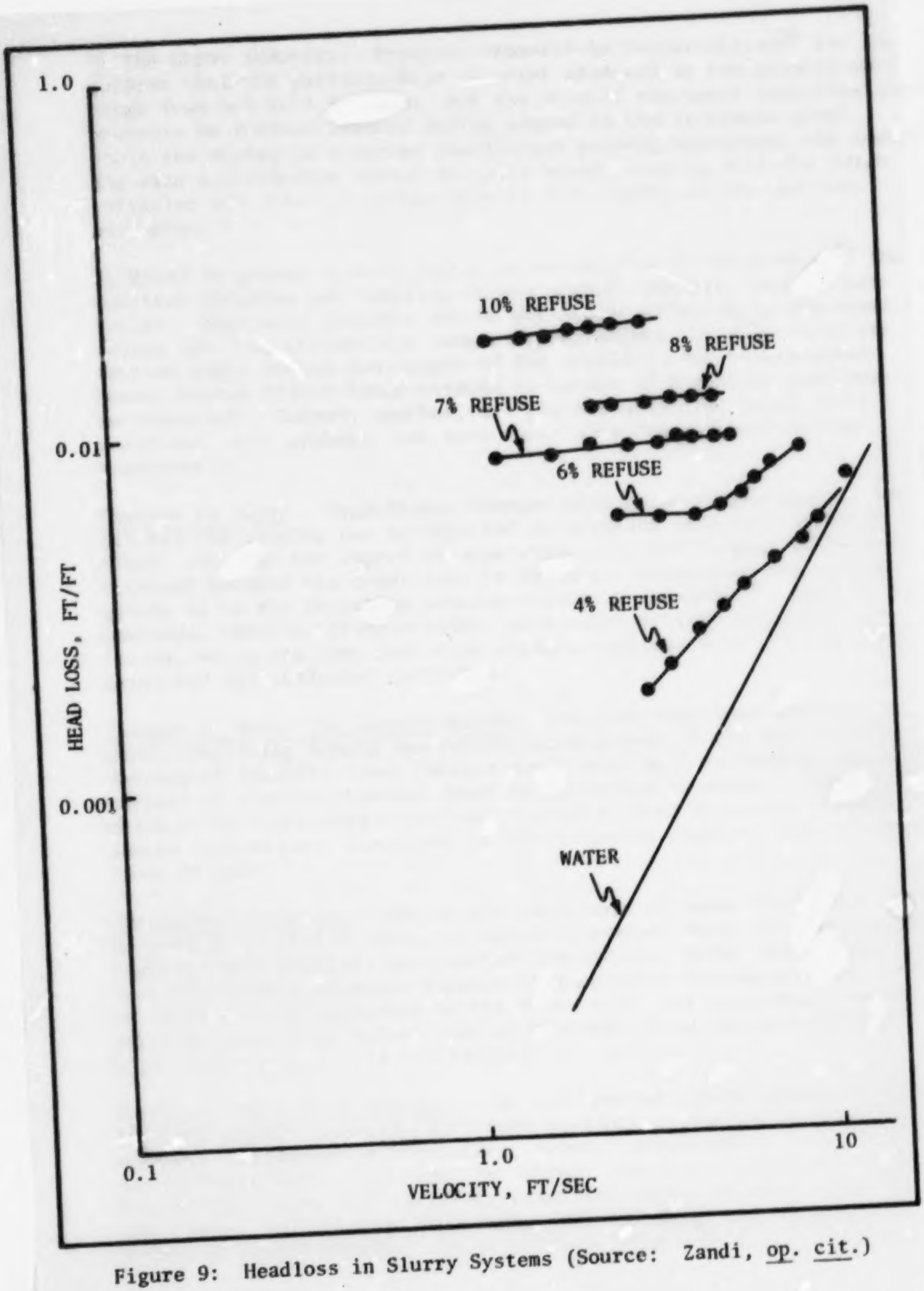

Figure 9: Headloss in Slurry Systems (Source: Zandi, op. cit.)

in the paper industry. Previous research by Foster-Miller[39] has indicated that the particle size of paper produced by the grinder will range from 0.5 to 1.5 inches, but the size of the paper particles would probably be further reduced during travel to the treatment plant. Since the mixing is a rather inefficient pulping operation, the resulting size distribution should be quite broad, ranging from the large particles of 1.0 to 1.5 inches down to 0.01 inches as the smallest particles.

If glass is ground up with particles as large as 0.375 inches,[40] the constant abrasion and tumbling should produce smaller, rounder particles. Rags will probably not be physically affected by transport unless the long strands are caught on protrusions, in which case attrition might reduce the length of the strands. But as discussed above, Foster-Miller found strands to be one of the major problems in transport. Rubber, leather, and plastic articles, being quite resilient, will probably not have their size changed much during transport.

Changes to Paper. Significant changes will occur to the paper. The ink and the coating can be expected to separate from the cellulose fiber, although the degree of separation attained remains to be determined because the conditions in the water suspension are not as severe as in the de-inking processes used by industry.[41] Some of the coatings, such as titanium oxide, will exist as fine suspended particles, while the inks and other organic coatings will exist as both dissolved and colloidal particles.

Changes in Metal Ion Concentration. Possible reactions between organic complexing agents and metals could result in the partial dissolving of specific ions. Metals could also be dissolved by the large variety of electro-chemical reactions possible in water. However, the evidence of quantitative analyses for metal ions in ground refuse-sewage suspensions, discussed in the following chapter, show no evidence of this.

Absorption Phenomena. Due to the large mass of paper fiber that will be present if ground refuse is added to sewage, there is a strong possibility that problems anticipated from grease, paint and oil may be less severe than expected because of absorption phenomena. The extent of these will be dependent on the fiber type, its coarseness and the particle size distribution, but again there is no concrete evidence upon which to base firm conclusions.

Potential Biological Changes. The addition of ground refuse to sewage may well result in a very different environment for the micro-organisms present. Chemicals in pesticides, aerosol propellents, heavy metals and petrochemicals would tend to inhibit biological activity, as would the bacteriostats used in paper, paint and rubber products. On the other hand, fertilizers, medicines, food and paper may enhance the growth of many organisms. Also, certain compounds (like vitamins or certain pesticides) and minerals (like cobalt) may be present in sufficient quantities to allow one type of organism to predominate. Moreover, the increased suspended solids will make available more surface area for organisms to grow on, and with the increased degradable matter may cause larger populations of micro-organisms to be present in sewers.

In turn, these larger populations may lead to more septic conditions with the resulting problems of sewer gas and corrosion. The Los Angeles experiments showed that the average flow velocity of the refuse solids was lower than the hydraulic flow velocity, (4 ft/sec rather than between 5 and 6 ft/sec).[42] Residence times of the refuse solids might therefore be longer than expected, which in turn would aggravate the odor and septicity problems.[43] However, these should be no greater than those already occurring in sewers with heavy garbage loads from garbage grinders.

Metcalf & Eddy,[44] as part of their laboratory studies on ground refuse in sewage, attempted to simulate and measure the conditions and changes during transport by mixing over three hours and running BOD tests at hourly intervals on the supernatants of the settled samples. No change in BOD was observed over the mixing times tested,[45] and the ratio of BOD of the filtered and unfiltered samples remained constant, indicating that the constituents of the oxygen demand did not change during transport from suspended to dissolved or vice versa.[46]

Conclusions

Validity of the Foster-Miller Results Under Real Conditions. Although the results of the Foster-Miller experiments appear generally favorable, their conclusions must be examined in the context of real situations that exhibit wide fluctuations around assumed average conditions.

The first point of importance is that actual solids concentrations will decrease as the distance of travel increases. Because of infiltration and contributions by nonresidential sewage producers, flows will tend to increase the nearer one gets to the treatment plant, and hence total solids concentrations will decrease. Figure 10 shows the concentration of total solids in sewage as a function of pounds per capita per day of refuse, plotted for different rates of per capita sewage production (or flows in sewers). It is clear from this Figure that under average conditions of refuse production (2.25 lb/cap/day), average total solids concentrations will range from about 0.7 percent in lateral sewers (where the flow may be as low as 30 gal/cap/day) to 0.3 percent in the major interceptors and at the treatment plant where flows are typically about 75 gal/cap/day.

Consequently, under average conditons, the range of solids concentrations to be encountered in the sewer system is below the limiting solids concentration for pipes flowing more than half full (i. e.,

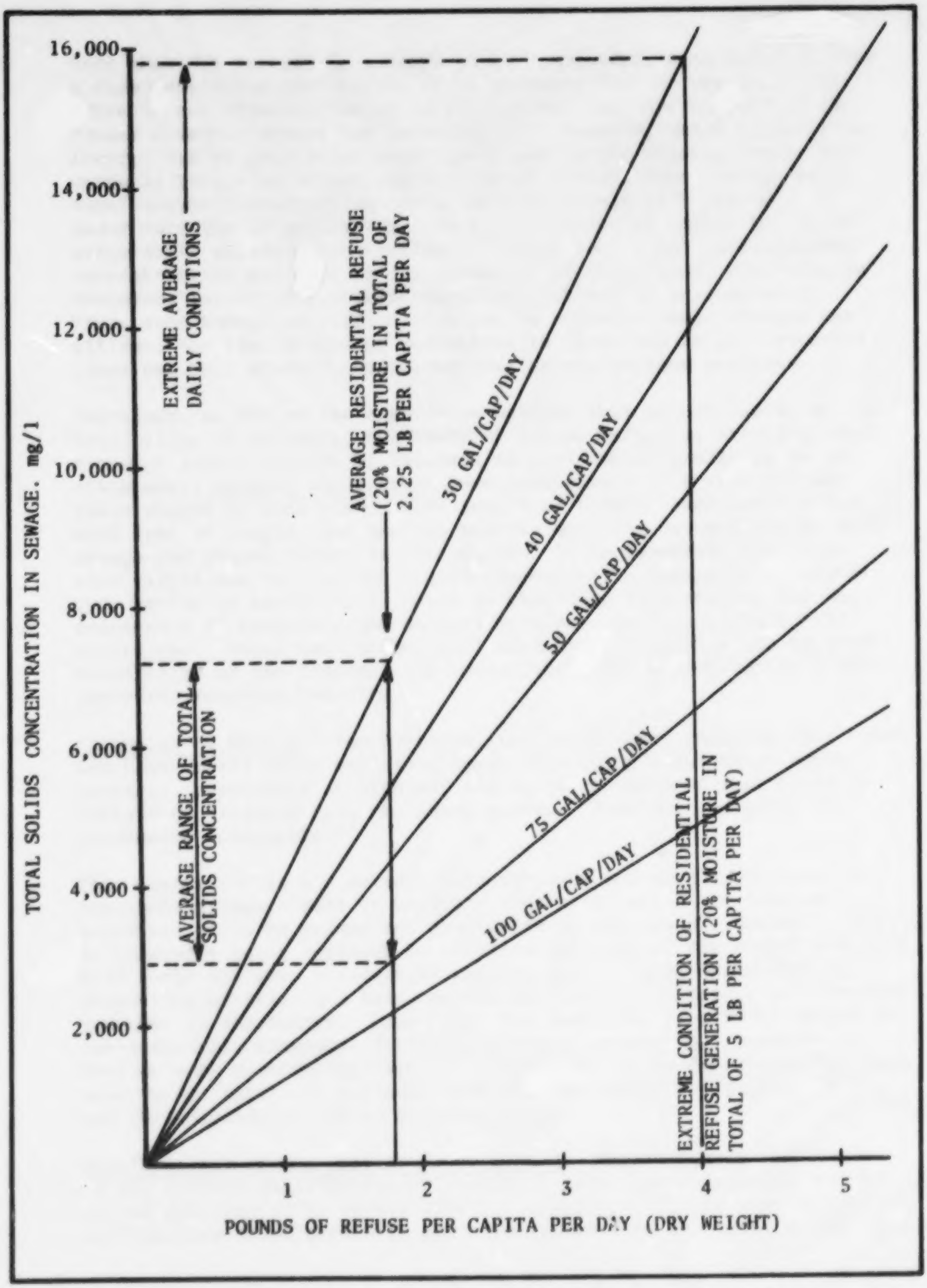

Figure 10: Total Solids Concentration as a Function of Per Capita Sewage and Refuse Generation Rates

less than 0.8 percent in a rough pipe). Moreover, even under extreme refuse generating conditions, it is probable that no problems will arise in the flows exceeding 50/gal/cap/day that are typical of the larger diameter sewers and interceptors. However, under higher-than-average refuse generation conditions, and in the lateral sewers that carry as little as 30 gal/cap/day, it is evident that average daily total solids concentration can be well in excess of 1 percent. A sewer carrying 30 gal/cap/day and 4 lbs/cap/day of refuse has an average daily solids concentration of 1.6 percent. But instantaneous concentrations may well be far in excess of this value, resulting in temporary losses of hydraulic capacity that may be unacceptable. Thus, even though no difficulties can be expected under average conditions, the time dependent variations in flows and solids concentrations may well produce conditions that create serious problems.

Therefore, we are of the considered opinion that no conclusion on the feasibility of hydraulic transport of ground refuse in existing small diameter sewers typical of laterals in residential areas can be possible until dynamic simulations have been made. At a very minimum, these should be made with a test length of 6-inch sewer several hundred feet in length, and include several building connections at which sewage and ground refuse is introduced. It is important that probable variations in flow and solids concentration should be simulated over cycles in excess of 24 hours so that long term effects and the occurrence of temporary but serious problems can be satisfactorily determined. These two factors will ultimately determine the technical feasibility of the concept, and should therefore be considered a most important research priority.

- Exclusion of Metals. The Foster-Miller experiments indicate that steel and heavy metal scrap may cause local deposition problems at appurtenances, especially at siphons, and it is recommended that these materials be excluded from the sewer system. Aluminum and glass are considered acceptable.[47]

This limitation is not serious because power and cost limitations to household grinders make it unlikely that steel and other ferrous materials could be ground and discharged to the sewer. Moreover, steel is gradually being replaced by aluminum for many of the containers that find their way into residential refuse, and it is probable that the proportion of steel and heavy metals in residential refuse will decline somewhat in the future. Conversely, the inability of gravity sewers to satisfactorily transport ferrous materials lessens the incentive to develop more powerful grinders.[48] Therefore, it is concluded that ferrous metals should be excluded from the wet refuse collection system, and periodically collected by other means.

Modifications to the Gravity Sewer System. Regardless of the outcome of any further experiments, it appears likely that some modifications to the existing sewer system will be necessary. But in view of the difficulties associated with pressure systems, it is unlikely that the modifications will entail pressurization.[49] Rather, it appears that gravity sewer systems built to modified design standards is the answer because of their superiority in solids carrying capacity under varying flow conditions, and their operational superiority for collecting flows from multiple sources. Such modified systems would involve steeper slope requirements, an increased use of lift stations, and built-in flushing arrangements. Any future extensions to the existing sewer system could readily be built to the new requirements; and because it is the expanding periphery of sewer systems that is most subject to the extreme conditions, major reconstruction in existing sections of the sewer system may not be necessary.

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49. With the possible exception of pressurized building connections.

CHAPTER IV

TREATMENT

Introduction

There is a critical lack of information on the physical-chemical characterization and treatability of ground refuse in sewage.[1] The only comprehensive study is that undertaken by Metcalf & Eddy[1] as part of the initial Foster-Miller contract, and some information is also available from the experiments conducted in the early sixties in Los Angeles.[2] We have carefully reviewed these studies and interpreted their results in the light of the conditions anticipated from our analysis of grinding and hydraulic transport.

However, the reader should bear in mind that the inferences drawn are based on only the two studies, neither of which represented typical conditions; the Boston sewage used in the Metcalf & Eddy study has a very high total solids content and is untypically weak, and used a single sample of ground refuse from a suburb of Cincinnati, Ohio; and the Los Angeles Study used refuse from which metal and glass had been removed and which was ground to 4-inch and 2-inch maximum size rather than the 1 or 1-1/2-inch size required for transport in small diameter sewers.

Some alternative indirect means of assembling information on the physical-chemical characterization were explored, but these yielded little of practical value. Leachates from sanitary landfills have been chemically analyzed by several authors,[3] but the conditions under which these are formed are so different to those which exist in a sewer system that no useful inferences are possible. Moreover, identification of exotic compounds in leachates is of little use because it is the concentrations that will largely determine any toxic effect on biological treatment or the ability of advanced waste treatment processes to remove them.

Another source of information would be direct quantitative analyses for specific potentially toxic compounds in residential solid waste. But no such information was found in the literature, and the studies that do address this subject tend to involve estimates rather than measurements.[4] But even if the concentrations of potentially toxic compounds in solid waste were known, information on the concentrations of the same compounds already present in sewage would also need to be known if conclusions were to be drawn about the impact of adding ground refuse.

Because so little information is available on the physical-chemical characterization of ground refuse in sewage, that which is available will be discussed together with the assessment of individual treatment processes. Physical-chemical changes during transport have already been discussed in Chapter III, and the discussion in this chapter confines itself to the probable impact at the treatment plant itself.

Preliminary and Primary Treatment

Bar Screens. Bar screens will continue to be needed with ground refuse as physical protection to the treatment facilities, with openings in the range of 1.5 to 2 inches. Refuse must in any case be ground to a size no greater than 1 to 1.5 inches because of potential clogging problems in the sewer system, and bar screen openings of less than 1 inch would be clearly troublesome.[5] Refuse grinding should not be an additional source of really large items if the grinders are properly designed.

Grit Removal. Grit removal facilities will definitely be required if ground refuse is added to sewage. The lack of grit removal would mean more difficult resource recovery, increased maintenance and equipment wear, and decreased usable volume in the sludge handling processes.

Figure 11 shows the amount of grit likely to be collected at the treatment plant, expressed in terms of the usual design parameter of cubic feet of grit per million gallons as a function of pounds of grit (metal and glass) produced per household per day, and per capita flows at the treatment plant.

The curves shown assume that no metal will be ground unless all the glass is ground; the change in slope is due to the different specific gravity of the metal and glass fractions. Because heavy metals must be excluded from the system,[6] it is likely that average grit quantities at the treatment plant will be in the range of 35 to 50 cubic feet per million gallons (cu ft/MG). This is somewhat higher than the average range of 0.3 to 25 cu ft/MG encountered at existing treatment plants equipped with grit chambers,[7] but is substantially below many of the peak daily grit quantities observed at existing facilities. It is possible that existing grit chambers could be adequate to handle the additional grit in ground refuse, but expansion of facilities may be necessary.

The design of a unit process to remove grit from a second refuse-sewage mixture may encounter two problems. In existing grit chambers, the separation efficiency can be so poor that 50 percent by weight of the removed grit can be organic.[8] Although this may be due to deficient operation rather than deficient design, the suspended solids of the ground refuse sewage mixture is orders of magnitude higher than that of normal sewage, and there is thus a distinct possibility of entrapment of large amounts of organics, especially paper fibers, with the removed grit. Furthermore, the organic particle size distribution will include particles much larger than normally encountered, and there is a substantial probability that some of these particles will settle out in the grit chamber. The other major problem is the retention of grit particles in the overflow. Even existing plants experience problems with grit due to inadequate removal, and the much higher suspended solids load with refuse grinding would allow for entrapment of a sizable portion of the grit in the overflow. One approach to solving these problems would be an aerated grit chamber with automatic mechanical removal. The aeration would classify the solids and result in a cleaner grit and less carry-over. The removed grit should be washed to remove organics and the wash water mixed with the overflow stream.

Screens. Metcalf & Eddy evaluated two mechanical separation devices for solids removal from primary sewage.[9] A Bauer hydrosieve, a stationary screen with no moving parts, was tested with screen sizes of 60, 30, and 10 mesh (slot openings of 0.06, 0.03 and 0.01 inches), using a slurry of 0.5 percent by weight of refuse in tap water. The 0.06-inch screen performed best, resulting in a sludge of 5 percent solids, and suspended solids and biochemical oxygen demand (BOD) concentrations in the effluent that were lower than those obtained by settling. Metcalf & Eddy felt that its high head-loss of up to 7 feet was its major disadvantage, but that the device merited further investigation, particularly as a first step in sludge dewatering.

The second screen device tested was a rotary drum screen manufactured by Zurn Industries. The screen was found to remove 98 percent of the suspended solids, independent of screen size (20, 60 and 100 mesh), but no opinion was offered as to its practical potential.

Although screens are in wide use by industry in a variety of applications, they have not been much used in municipal wastewater treatment. Metcalf & Eddy reports that the Bauer hydrosieve was recently installed as a sole means of primary treatment at a municipal sewage treatment plant,[10] and the writers feel that such devices should definitely be included in any pilot scale evaluations of alternative processes for the treatment of ground refuse-sewage mixtures. As we shall see below, there are indications that primary sedimentation may not be effective in removing small cellulose fibers, and preliminary screening may therefore be required because these fibers are not readily amenable to biological degradation.

Suspended Solids Concentrations. In considering primary settling as a means of treatment, knowledge of the suspended solids concentrations in the influent is necessary. Unfortunately, Metcalf & Eddy experienced considerable difficulty in making suspended solids determinations of unsettled ground refuse-sewage mixtures,[11] and the reports on the Los Angeles experiments contained no quantitative information on this subject. However, one can obtain some rough estimates by a solids balance, as shown on Figure 12. A typical daily per capita refuse quantity of 2.25 lb may[12] result in 1.575 lb of dry solids ground and entering the sewers per capita per day. Of this, about 0.17 lb will be grit (see above, "Grit Removal") and from the Metcalf & Eddy measurements of dissolved solids in the supernatant of the settling tests one obtains

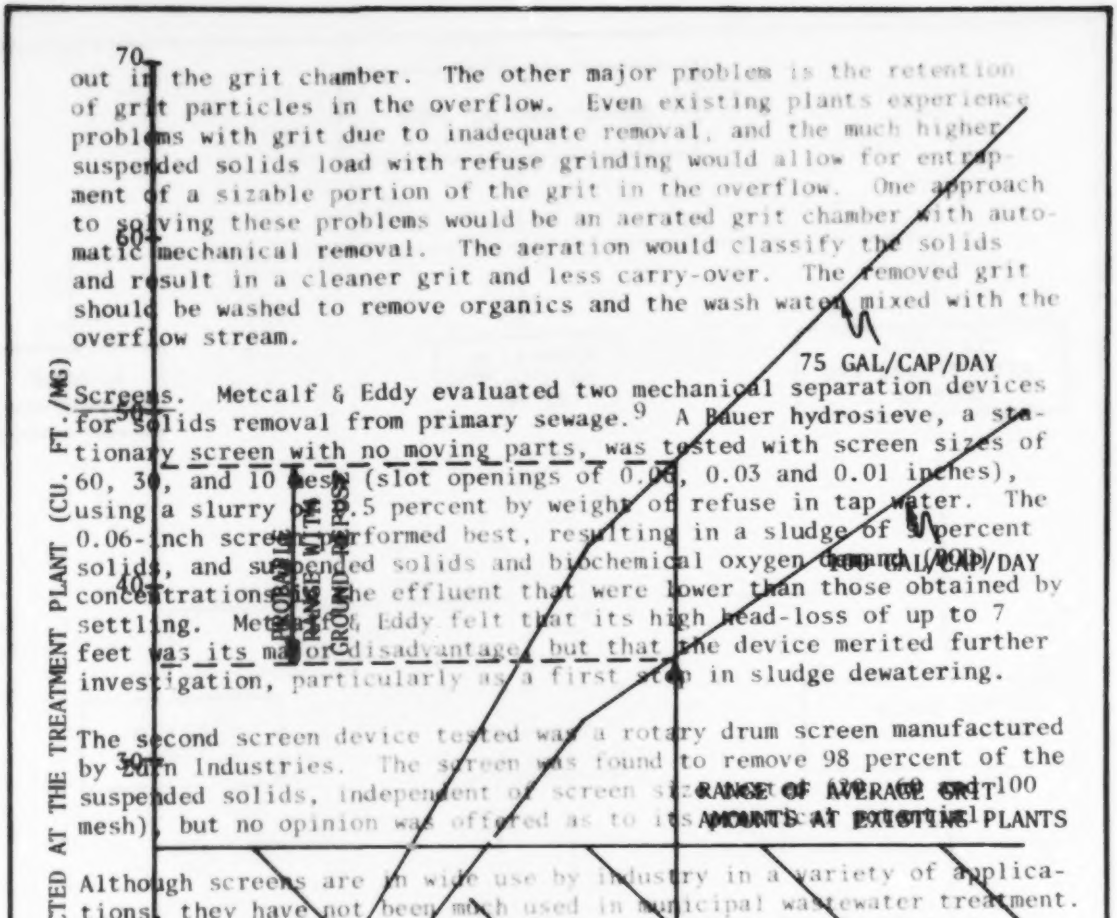

Figure 11: Anticipated Grit Quantities

out in the grit chamber. The other major problem is the retention of grit particles in the overflow. Even existing plants experience problems with grit due to inadequate removal, and the much higher suspended solids load with refuse grinding would allow for entrapment of a sizable portion of the grit in the overflow. One approach to solving these problems would be an aerated grit chamber with automatic mechanical removal. The aeration would classify the solids and result in a cleaner grit and less carry-over. The removed grit should be washed to remove organics and the wash water mixed with the overflow stream.

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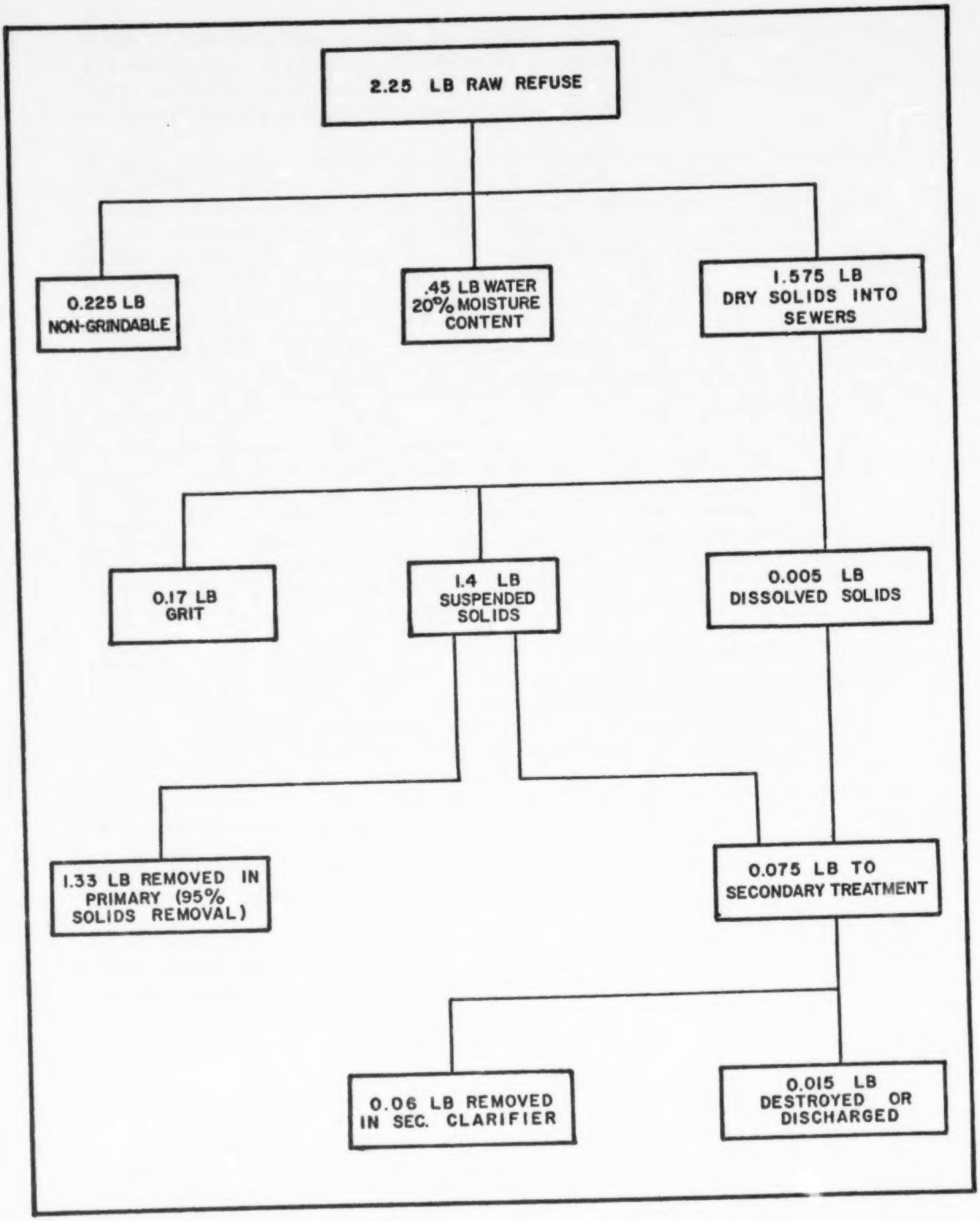
2.25 LB RAW REFUSE
0.225 LB NON-GRINDABLE
.45 LB WATER 20% MOISTURE CONTENT
1.575 LB DRY SOLIDS INTO SEWERS
0.17 LB GRIT
1.4 LB SUSPENDED SOLIDS
0.005 LB DISSOLVED SOLIDS
1.33 LB REMOVED IN PRIMARY (95% SOLIDS REMOVAL)
0.075 LB TO SECONDARY TREATMENT
0.06 LB REMOVED IN SEC. CLARIFIER
0.015 LB DESTROYED OR DISCHARGED

Figure 12: Mass Balance for Refuse Solids, in lb/cap/day

0.005 lb of dissolved solids per capita per day. Consequently, 1.4 lb/cap/day will be in the form of suspended solids. This converts to 1678, 2238 and 3357 mg/l at 100, 75 and 50 gals/cap/day of sewage at the treatment plant inflow, respectively.

Primary Settling. The Los Angeles experiments indicated that ground refuse in sewage settled readily in a primary sedimentation basin. However, a noticeable increase in floating matter was noted, consisting of materials such as styrofoam, plastics, leaves, small twigs and garden clippings. Metcalf & Eddy reported that ground refuse-sewage suspensions did not settle well, but that the nonsettleable mass tended to float and remain at the surface even after two hours.[13] Both studies agree that the floatables can easily be removed from a primary sedimentation basin by somewhat strengthened skimming devices. Settling studies conducted by Metcalf & Eddy indicated that a high percentage of suspended solids was removed within a 1-hour detention time: the suspended solids in the supernatant increased from 105 mg/l with no refuse to 200 mg/l with 1 percent ground refuse, and volatile suspended solids from 50 mg/l with no refuse to 185 mg/l with 1 percent ground refuse.[14] Tests with refuse concentrations of 0.25 and 0.5 percent ground refuse, which is the range actually expected (see Figure 10), showed suspended solids concentrations that were less than those with no refuse added.[15] The settleability tests resulted in a sludge of about 5 percent solids content, which is somewhat lower than that observed at many existing treatment plants.[16]

Whitney concluded on the basis of the Los Angeles experiments that primary settling would remove 95 percent of the additional suspended solids loading. Using the suspended solids concentration in the influent calculated previously, the effluent from the primary settler would contain an additional 84, 112 or 168 ppm of suspended solids at 100, 75 and 50 gal/cap/day, respectively, due to the addition of ground refuse. But the range of suspended solids in the effluents of existing primary settlers is 20 to 160 ppm,[17] and thus the additional suspended solids concentration entering secondary treatment due to refuse grinding would be little more than the variations exhibited by existing primary effluents.

With respect to the BOD in the primary settler effluent, Metcalf & Eddy found that the BOD in the supernatant after 1 hour settling could be expressed by the equation[18]

$$y(C) = y(0) + 143.3\ C \qquad [2]$$

where C is the percentage of ground refuse in sewage by weight, y(C) is the BOD in mg/l at that concentration C, and y(0) is the BOD in mg/l with no refuse added. This relationship has been replotted on Figure 13, expressed in terms of the per capita quantities of refuse and sewage generated. Also shown are the estimated increases in BOD resulting from the installation of garbage grinders at Aurora,[19] Colorado (with 60 percent of households so equipped) and at Jasper, Indiana[20] (with 92 percent of households so equipped), the estimates

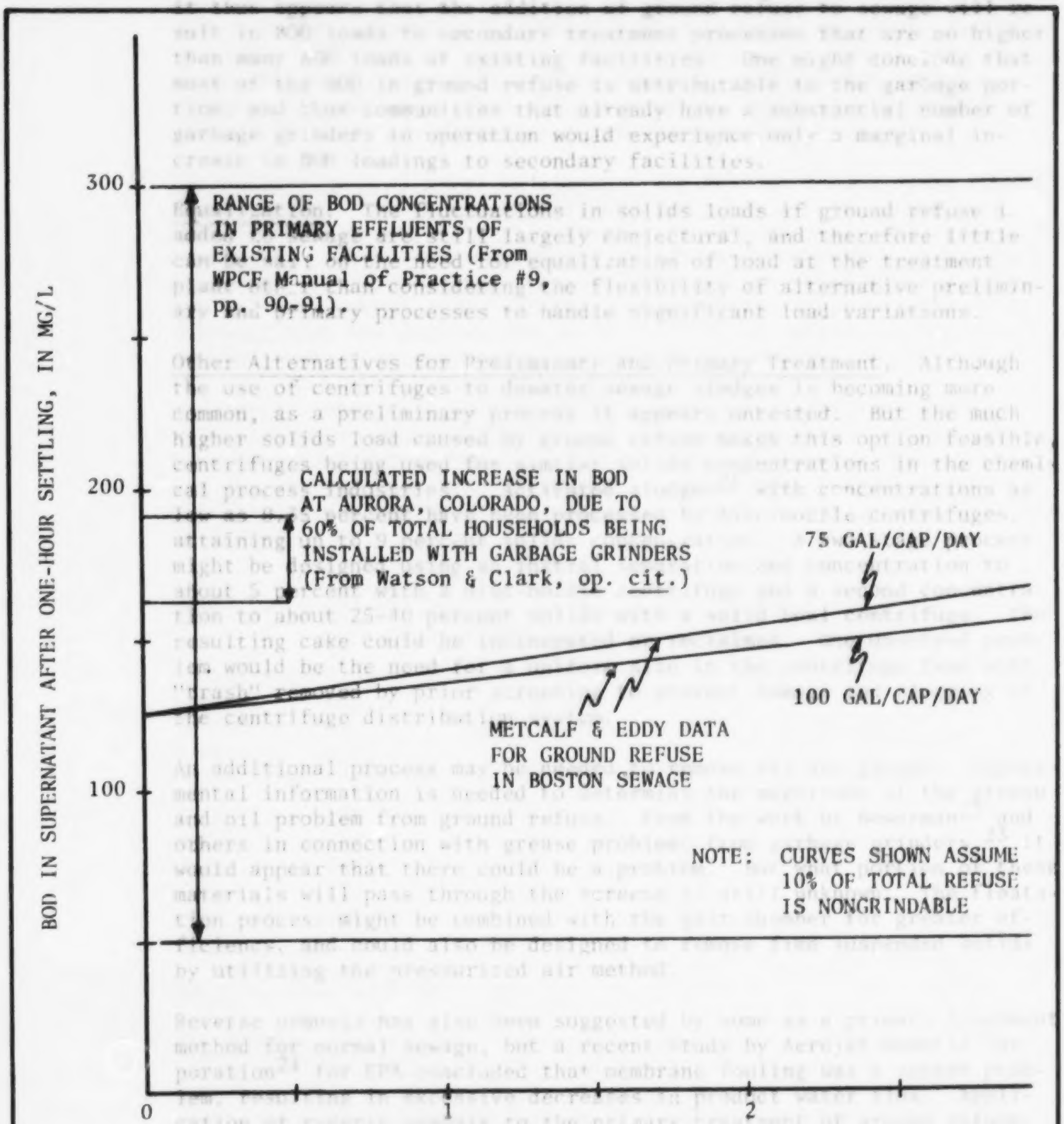

Figure 13: Expected BOD Concentrations in Primary Effluents

based on a 40 percent removal of the measured BOD values of the treatment plant influent in the primary settler.

It thus appears that the addition of ground refuse to sewage will result in BOD loads to secondary treatment processes that are no higher than many BOD loads at existing facilities. One might conclude that most of the BOD in ground refuse is attributable to the garbage portion, and thus communities that already have a substantial number of garbage grinders in operation would experience only a marginal increase in BOD loadings to secondary facilities.

Equalization. The fluctuations in solids loads if ground refuse is added to sewage are still largely conjectural, and therefore little can be said on the need for equalization of load at the treatment plant other than considering the flexibility of alternative preliminary and primary processes to handle significant load variations.

Other Alternatives for Preliminary and Primary Treatment. Although the use of centrifuges to dewater sewage sludges is becoming more common, as a preliminary process it appears untested. But the much higher solids load caused by ground refuse makes this option feasible, centrifuges being used for similar solids concentrations in the chemical process industries. Activated sludges[21] with concentrations as low as 0.35 percent have been processed by disc-nozzle centrifuges, attaining up to 9 percent solids concentration. A two-stage process might be designed using an initial separation and concentration to about 5 percent with a disc-nozzle centrifuge and a second concentration to about 25-40 percent solids with a solid bowl centrifuge. The resulting cake could be incinerated or reclaimed. One unsolved problem would be the need for a uniform size in the centrifuge feed with "trash" removed by prior screening to prevent damage and plugging of the centrifuge distribution system.

An additional process may be needed to remove oil and grease. Experimental information is needed to determine the magnitude of the grease and oil problem from ground refuse. From the work by Bowerman[22] and others in connection with grease problems from garbage grinders,[23] it would appear that there could be a problem. But what portion of these materials will pass through the screens is still unknown. The floatation process might be combined with the grit chamber for greater efficiency, and could also be designed to remove fine suspended solids by utilizing the pressurized air method.

Reverse osmosis has also been suggested by some as a primary treatment method for normal sewage, but a recent study by Aerojet-General Corporation[24] for EPA concluded that membrane fouling was a severe problem, resulting in excessive decreases in product water flux. Application of reverse osmosis to the primary treatment of ground refuse-sewage mixtures is therefore quite remote.

Secondary Treatment

The foregoing analysis of preliminary and primary treatment allows the conclusion that the influents to secondary biological treatment likely to be encountered if ground refuse is added to sewage should be little different to those presently encountered. BOD loads should be little higher than those found in cities where garbage grinders already exist, and suspended solids loads should exhibit only small increases with proper primary process design.

Amenability to Biological Treatment. The Metcalf & Eddy study showed every indication that the primary effluent from ground refuse in sewage could be satisfactorily treated by conventional activated sludge treatment. Long-term measurements of BOD exertion showed no evidence of inhibitory effects, and the rate constant was found to be 0.09 per day for both sewage alone and the ground refuse-sewage mixture,[25] indicating that the supernatant of the settled suspensions tested resembled that of settled sewage in its rate of degradation.

Nutrients. Metcalf & Eddy found that both phosphorus and nitrogen were present in adequate quantities, as shown on Table 5. The addition of ground refuse had no effect on total phosphorus concentration, and the nitrogen (as total Kjeldahl Nitrogen, TKN) increased only slightly, due possibly to the nitrogen content in the garbage fraction of refuse.

Table 5: Nutrients Present and Theoretically Required in the Supernatant of Ground Refuse in Sewage

Percent Ground Refuse	BOD in mg/l	Theoretical Nutrient Requirements, in mg/l		Nutrients Present, in mg/l	
		N	P	TKN	Total P
0	120	6	1.2	15	7.4
0.25	154	8	1.5	17	7.4
0.50	187	9	1.9	20	7.4
0.75	221	11	2.2	22	7.5
1.0	255	13	2.6	24	7.5
1.25	289	14	2.9	26	7.5

Source: Metcalf & Eddy, *op. cit.*, p. 3-18.

The Problem of Toxicity. Concern has been expressed over the possibility that the addition of ground refuse to sewage might bring materials to the sewage treatment plant that are toxic to the microorganisms normally encountered in biological treatment. If this were the case, then refuse grinding and wet transport would be incompatible in all cities that had biological sewage treatment facilities, which would make the concept practically infeasible. However, there is no evidence in either the Los Angeles or the Metcalf & Eddy studies that potentially toxic materials are present in concentrations higher than those to be found in existing sewage.

Metcalf & Eddy also conducted tests on heavy metal concentrations in the supernatant of settled ground refuse in sewage, the results of which are shown on Table 6. Of the metals examined, only aluminum showed any increase in the presence of 0.5 percent by weight of ground refuse, and the concentrations of mercury, copper, iron and zinc actually decreased. The explanation for this decrease is not quite clear, but one may conjecture that in the presence of the high solids concentrations increased absorption phenomena during transport and primary settling may be responsible.

Table 6: Concentration of Metals

	Supernatant of Settled Boston Sewage	Supernatant of Settled Ground Refuse in Boston Sewage, 0.5% by Weight
Mercury	0.0068 mg/l	0.0043 mg/l
Copper	0.50 mg/l	0.45 mg/l
Chromium	<0.10 mg/l	<0.10 mg/l
Iron	2.20 mg/l	1.50 mg/l
Lead	<0.05 mg/l	<0.05 mg/l
Zinc	0.42 mg/l	0.38 mg/l
Cadmium	<0.05 mg/l	<0.05 mg/l
Nickel	<0.10 mg/l	<0.10 mg/l
Aluminum	0.31 mg/l	1.10 mg/l
Beryllium	0.00 mg/l	0.00 mg/l
Antimony	<0.10 mg/l(a)	<0.10 mg/l(a)
Selenium	<0.0001 mg/l	<0.0001 mg/l

a. None detected (0.10 = limits of detection)

Source: Metcalf & Eddy, op. cit., p. 3-22

In the light of existing knowledge of the effects of heavy metal treatment in sewage one may conclude that no major problems will be encountered with ground refuse additions. Many municipal treatment plants receive much higher metal concentrations on almost a continuous basis, and it is reported that chromium, zinc, copper, and nickel concentrations in the range of 1 to 9 mg/l, including slug discharges within this range, do not significantly impair the efficiency of secondary biological treatment.[26] Another recent study suggests that silver and nickel were toxic to sewage bacteria at concentrations in excess of 10 mg/l, and chromium, zinc and copper did not show any toxic effects below 25 mg/l.[27] Failure of anaerobic digestors in the presence of heavy metals is reported by several authors,[28] but the critical concentrations generally exceeded 10 mg/l. Thus it is not surprising that the oxygen uptake tests conducted by Metcalf & Eddy showed no evidence of toxic conditions at refuse concentrations of up to 1.25 percent by weight. Oxygen uptake did increase as the percentage of refuse was increased, but this was anticipated as more food was made available. Metcalf & Eddy concluded that the organics present were utilized as food source without difficulty.[29]

The Mercury Problem. Mercury is one of the most toxic of all heavy metals and several recent studies have focused on mercury levels in the aquatic environment and on the presence of mercury in sewage and its effect on biological treatment processes.[30] The possibility of aggravating these problems by adding ground refuse to sewage is therefore not unimportant. Unfortunately, there does not appear to be any information on the mercury content of residential refuse in the literature, and only some indirect calculations can provide any confirmation of Metcalf & Eddy's single measurement.

The annual consumption of mercury in the United States is shown on Table 7, broken down by category of use, as given in the 1971 Edition of the Chemical Statistics Handbook.[31] Also shown for each category is an estimate of the maximum quantities of mercury that might be present in residential refuse, derived by multiplying total consumption by an assumed percentage figure. On the hypothesis that this mercury is to be found in the refuse of the 160 million urban residents, and that the per capita dry weight of refuse generated is 1.8 lb/day, then the maximum concentration of mercury in residential refuse is seen to be:

$$\frac{0.766 \times 10^{6} \left[\frac{\text{lbs Hg}}{\text{year}}\right]}{1.8 \left[\frac{\text{lb Refuse}}{\text{cap day}}\right] \times 365 \left[\frac{\text{days}}{\text{year}}\right] \times 160 \times 10^{6} \left[\text{cap}\right]} \tag{3}$$

$$= 7.28 \times 10^{-6} \left[\frac{\text{lb Hg}}{\text{lb Refuse}}\right]$$

which, at a sewage loading of 100 gal/cap/day, would result in a concentration of mercury at the treatment plant inflow of

$$\frac{7.28 \times 10^{-6} \left[\frac{\text{lb Hg}}{\text{lb Refuse}}\right] \times 1.8 \left[\frac{\text{lb Refuse}}{\text{cap day}}\right] \times 454 \left[\frac{\text{gms}}{\text{lb}}\right]}{100 \left[\frac{\text{gal}}{\text{cap day}}\right] \times 3.785 \left[\frac{\ell}{\text{gal}}\right]} \tag{4}$$

$$= 15.71 \times 10^{-6} \left[\frac{\text{gms}}{\ell}\right]$$

Table 7: Consumption of Mercury in the United States

	1969 Consumption in 1000 lb.	Assumed Maximum Percent in Residential Refuse	Maximum amounts of Mercury in Residential Refuse in 1000 lb.
Agriculture (including fungicide and bactericides for industrial purposes)	204.36	10%	20.40
Amalgamation	14.82	10%	1.48
Catalysts	224.80	10%	22.40
Dental Preparations	232.02	20%	46.40
Electrical Apparatus	1,417.40	20%	283.40
Electrolytic (for chlorine and caustic soda manufacture)	1,574.72	0%	0.00
Laboratory use	155.11	0%	0.00
Industrial and Control Instruments	530.55	0%	0.00
Paint - Antifouling	18.54	10%	1.85
Paint - Mildew Proofing	720.94	10%	72.09
Paper and Pulp Manufacture	42.40	100%	42.40
Pharmaceuticals	55.02	100%	55.02
Other	736.36	30%	220.90
TOTALS	5,927.04		766.34

Source: Chemical Statistics Handbook, op. cit., p. 307.

or 0.015 mg/l. This upper bound should be compared to the values measured by Metcalf & Eddy (0.0068 mg/l for Boston sewage, 0.0043 mg/l for supernatant of settled ground refuse) as shown on Table 6, and the mercury concentrations in some sewage treatment plant influents that have a substantial industrial waste content, as shown, for example, on Table 8. It is quite possible, therefore, that the mercury concentrations encountered in the presence of ground refuse may be significantly higher than currently encountered in sewage; although the simplified calculations of the upper bound as presented here and Metcalf & Eddy's single determination should clearly be replaced by a series of quantitative measurements of statistical validity before final judgments of the seriousness of the problem are ventured.

Table 8: Mercury Levels in Raw Wastewater at Municipal Wastewater Treatment Plants in Michigan, April 14, 1970

Location	Mercury mg/l
Lansing	0.004
Ann Arbor	0.002
Wayne Company	0.002
Pontiac-Auburn	0.002
Cadillac	0.010
Muskegon	0.002

Source: Ghosh and Zugger, op. cit., p. 424.

Conclusions. The Metcalf & Eddy study shows no evidence of any serious problems in conventional activated sludge treatment. But, although there is every indication of feasibility, a bench scale treatability study using a range of representative ground refuse and sewage samples must remain an urgent research priority. The fact that no toxic or inhibitory effects were found in the single study performed is no basis for a generalization; but the same absence of such effects is nevertheless an encouraging sign that clearly justifies further and detailed investigation.

The absence of inhibitory and toxic effects is not unexpected. As noted in Chapter I, the possibility of exotic compounds being added to the sewage treatment plant from residuals attached to aerosol containers, make-up bottles, detergent and cleaning containers must be placed in the perspective that much of the contents of these containers already finds its way to the sewage treatment plant by way of shower, bath and laundry effluents. The recommended method if disposing of surplus medicines is already by flushing into the sewage system. And the potential problem of latex paints attached to empty paint containers should be put in the perspective that paint brushes, rollers, and spray trays are already washed and cleaned under water, with washings disposed of in the kitchen sink. Indeed, this is a strong selling and advertising point of these water-based latex paints. Nevertheless, as illustrated by the admittedly simplified calculations for mercury concentration, further quantitative analyses on actual ground refuse-sewage samples must be available before a definitive judgment on the problem of hazardous and toxic materials is made.

Sludge Handling and Disposal

The problems of sludge handling and subsequent disposal are complex, and are the subject of a separate technical report.[32] The major findings of the detailed analyses contained in this separate report can be summarized as follows:

1. The cost of dewatering and disposal of the sludge generated at a sewage treatment facility handling ground refuse is in the range of $15 to $25 per ton of dry solids, and substantially below that of a treatment facility handling only sewage solids. The major determinants of total per ton cost are per capita refuse generation rates and the number of persons served by the facility.

2. Economies of scale and the predominance of a more readily dewaterable primary sludge are the major reasons for the relatively low unit costs. The sludge handling facilities of a secondary plant handling an average residential refuse generation rate correspond to the size of the facilities handling only primary sewage sludge generated by 9 to 12 times the number of inhabitants.

3. Because of the much higher ratio of primary to secondary sludge at a facility treating ground refuse, separate treatment chains for the primary and secondary sludges are not recommended. The small amount of secondary sludge, when mixed with the primary sludge, will have little or no impact on the thickening and dewatering characteristics of the primary sludge that would be rich in refuse solids.

4. The most promising sludge handling process chain includes thickening, vacuum filtration and disposal by landfill. Anaerobic digestion prior to vacuum filtration would be economic if the market price of methane were to exceed about $0.80 per 1000 cu ft, and incineration should also be considered if landfill conditions are unfavorable. Advanced technologies, such as pyrolysis, were not investigated due to lack of appropriate data.

Advanced Waste Treatment

It should be stressed at the outset that the inferences drawn in this section are even more conjectural than those of the previous sections, because they are based on even less concrete evidence than there is available for conventional treatment. Direct assessments of the impact on, or suitability of specific advanced waste treatment processes are simply not possible at the present time. All that can be done is to assess the probability that certain types of processes, for example for nutrient removal, or for the removal of nonbiodegradable organics, will be required because of the addition of ground refuse, or how these processes might be affected if already necessary or present at a treatment plant. The inferences drawn from the scanty evidence available should therefore be treated with due caution.

Tertiary Polishing. The effluent quality from conventional secondary biological treatment of ground refuse in sewage is unknown as no bench scale tests have been conducted. On the basis of the probable influent quality to secondary treatment (see above), one would expect slightly higher BOD and suspended solids concentrations. However, operational modifications at an existing facility could probably bring BOD and suspended solids concentrations to their former levels. If upgrading at an existing facility were needed, microstraining of the secondary effluent would be a very likely option. Experience with microstrainers shows them to be the most economical of upgrading techniques, with routine BOD and suspended solids removals of 50-70 percent.[33]

If the BOD and suspended solids in the influent were increased at an existing secondary facility by 50 and 100 percent respectively, say from 100 to 200 ppm suspended solids (SS) and from 150 to 225 ppm BOD,[34] then assuming an unchanged removal performance of 75 percent, the secondary effluent concentrations would be 50 ppm and 56 ppm BOD as against the former concentrations without adding ground refuse of 25 ppm SS and 37 ppm BOD. Thus a polishing device with a 50 percent removal performance would bring the secondary effluents back to at least their former quality.

Metcalf & Eddy[35] also made measurements of COD in the supernatant of the settled refuse suspensions, and their results, recomputed as a function of pounds per capita of day of refuse, are shown on Figure 14. The much higher increase in COD over BOD can be attributed to presence of fine cellulose fibers. The cellulose linkages are not easily broken down by the bacteria, whereas the dichromate used in COD determination is more effective. This explanation, of course, implies that secondary biological treatment will be equally ineffective in breaking down the cellulose fines, and COD levels in the secondary effluents will be substantially higher. Screens rather than clarifiers might prove more effective in primary treatment to reduce the level of cellulose fines, or micro-strainers of suitable size or screens developed by the paper industry for fiber recovery processes might be effective as a tertiary treatment step. However, in the absence of more detailed experimental treatability studies, this is all quite conjectural, and the need for further research on this aspect is clear.

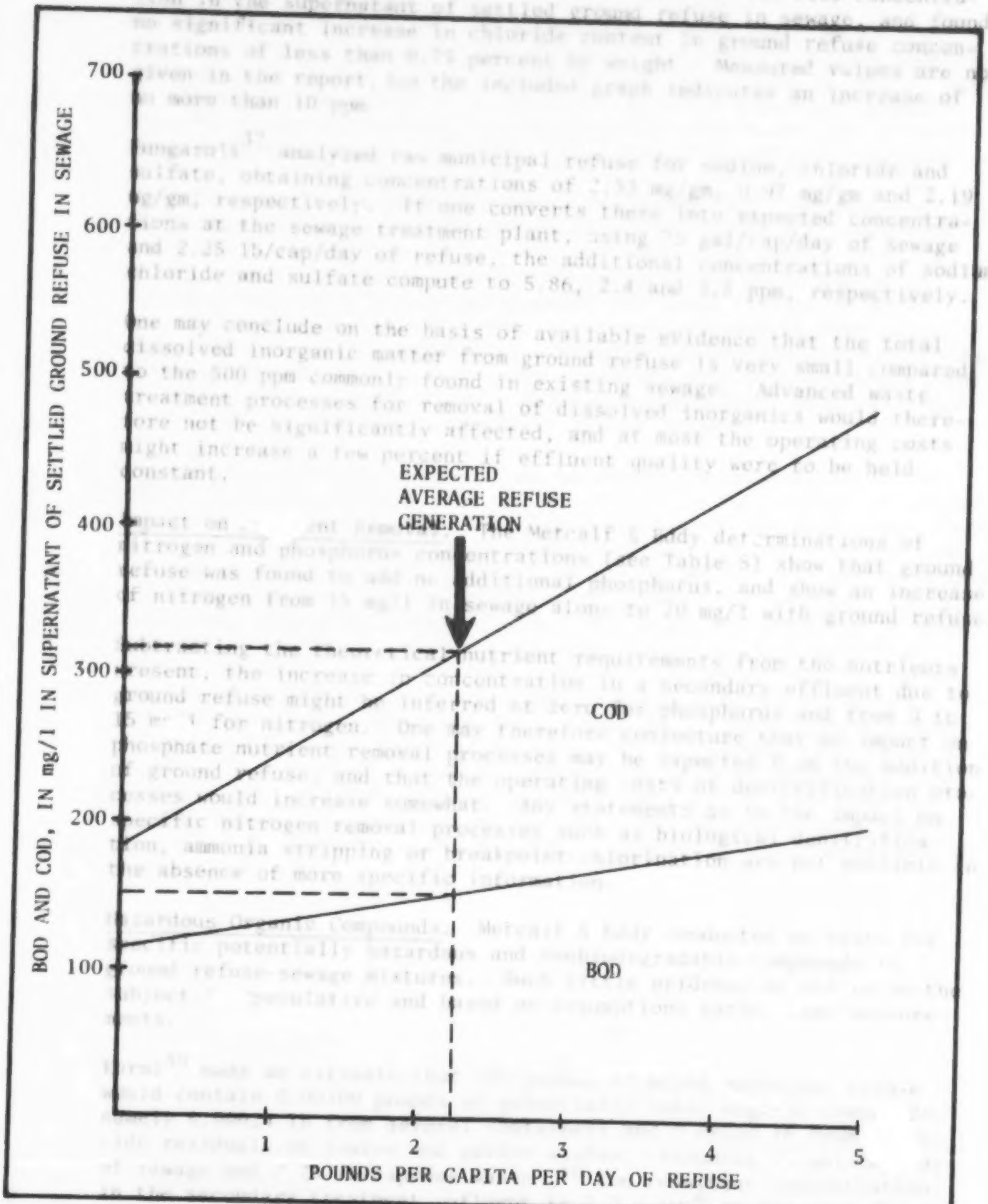

Figure 14: BOD and COD Concentrations

Dissolved Inorganics. Metcalf & Eddy[36] measured chloride concentration in the supernatant of settled ground refuse in sewage, and found no significant increase in chloride content in ground refuse concentrations of less than 0.75 percent by weight. Measured values are not given in the report, but the included graph indicates an increase of no more than 10 ppm.

Fungaroli[37] analyzed raw municipal refuse for sodium, chloride and sulfate, obtaining concentrations of 2.33 mg/gm, 0.97 mg/gm and 2.19 mg/gm, respectively. If one converts these into expected concentrations at the sewage treatment plant, using 75 gal/cap/day of sewage and 2.25 lb/cap/day of refuse, the additional concentrations of sodium, chloride and sulfate compute to 5.86, 2.4 and 5.5 ppm, respectively.

One may conclude on the basis of available evidence that the total dissolved inorganic matter from ground refuse is very small compared to the 500 ppm commonly found in existing sewage. Advanced waste treatment processes for removal of dissolved inorganics would therefore not be significantly affected, and at most the operating costs might increase a few percent if effluent quality were to be held constant.

Impact on Nutrient Removal. The Metcalf & Eddy determinations of nitrogen and phosphorus concentrations (see Table 5) show that ground refuse was found to add no additional phosphorus, and show an increase of nitrogen from 15 mg/l in sewage alone to 20 mg/l with ground refuse.[38]

Subtracting the theoretical nutrient requirements from the nutrients present, the increase in concentration in a secondary effluent due to ground refuse might be inferred at zero for phosphorus and from 9 to 15 mg/l for nitrogen. One may therefore conjecture that no impact on phosphate nutrient removal processes may be expected from the addition of ground refuse, and that the operating costs of denitrification processes would increase somewhat. Any statements as to the impact on specific nitrogen removal processes such as biological denitrification, ammonia stripping or breakpoint chlorination are not possible in the absence of more specific information.

Hazardous Organic Compounds. Metcalf & Eddy conducted no tests for specific potentially hazardous and nonbiodegradable compounds in ground refuse-sewage mixtures. Such little evidence as exists on the subject is speculative and based on assumptions rather than measurements.

Kormi[39] made an estimate that 100 pounds of mixed municipal refuse would contain 0.00309 pounds of potentially toxic organic compounds, namely 0.00024 lb from aerosol containers and 0.00250 lb from pesticide residuals on leaves and garden wastes. Assuming 75 gal/cap/day of sewage and 2.25 lb/cap/day wastes,[40] the resultant concentration in the secondary treatment influent is 7.7×10^{-8} gms/gm or 0.077 mg/l. If all the potentially toxic materials were indeed toxic, then this concentration of 77 ppb would certainly have some significant impact. If endosulfan or dieldrin were to account for even 10 percent of this, and were to be discharged into a receiving stream carrying 10 times the flow of the treatment plant effluent, then the downstream concentration would be 7.7×10^{-10} gms/gm or 0.77 ppb. This is in the range of concentrations quoted as being toxic for fish and other aquatic life.[41] If such concentrations were indeed encountered, an advanced waste treatment process to remove these compounds would be required.

Although Kormi's estimates are based on assumptions that may well be questioned, it is clear that the possibility of such nonbiodegradable compounds being introduced into the environment by way of grinding refuse into sewage makes some actual measurements quite urgent if the need for a suitable advanced waste treatment process is to be realistically assessed. However, such compounds may already exist in sewage for reasons previously stated, and therefore concentration measurements of the same compounds should be made on the sewage alone as well as with ground refuse. Only such comparative data can yield information on the impact of adding ground refuse.

Conclusion. With the exception of hazardous, nonbiodegradable compounds, one may conclude that the addition of ground refuse to sewage has no major impact on the choice or operation of advanced waste treatment processes. No advanced treatment process not required for treating sewage alone would be required if ground refuse were added, because minor modifications in the operation of primary and secondary facilities could generally bring effluents to the quality produced by treatment of sewage alone. Because advanced waste treatment processes will probably be required anyway under the new water quality legislation, the only impact to be expected from the addition of ground refuse is slightly higher operating costs due to the slightly higher loads involved. But once again the reader is reminded that these inferences are drawn from the limited experimental evidence available at this time. Thus no definitive conclusions can be made pending further laboratory studies; and in particular much more information is needed on the presence of hazardous, nonbiodegradable compounds in residential refuse.

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CHAPTER IV

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CHAPTER V

RESOURCE RECOVERY

Introduction

The 1970 amendments to the solid waste disposal act,[1] which shifted much of the emphasis in solid waste management research from disposal to recycling and reuse, and the growing citizen interest and concern in resource recovery, both stress the importance of carefully considering the impact of any new solid waste management concept on resource recovery. However, existing market conditions are generally quite unfavorable to recycling of the materials that constitute municipal solid wastes, and such markets as do exist tend to be characterized by fluctuations that make generalizations of potential dollar benefits very difficult. Although the reasons for these unfavorable conditions are understood, great uncertainty still surrounds the effectiveness of legislative measures to correct these deficiencies. As noted by Darney and Franklin,[2] the reasons why virgin materials costs are relatively low and recycled materials relatively high is that the market mechanism fails to reflect the true socioeconomic costs of virgin materials, nor does it credit recycled materials with its social benefits. Virgin materials producers enjoy depletion allowances, they do not pay the full costs of environmental degradation created by their mining, harvesting, transportation, and processing activities, and they are not charged for generating solid wastes. On the other hand, secondary materials are not credited with conservation of natural resources, favorable contributions to foreign trade balance, low pollution generation in reprocessing, and removal of materials from the solid waste stream.[3]

Another reason for the importance of an assessment of resource recovery potential is that much of the enacted and proposed legislation to redress these deficiencies in the market mechanism is directed towards aiding recycling under existing solid waste management practices, whereas new approaches may be necessary under the radically new solid waste management concepts evaluated in this report.

The major potential opportunities for resource recovery from residential refuse if ground and discharged to the sewers are in the recovery of paper fiber, glass, aluminum, ferrous metals and energy. Opportunities for the recovery of textiles, plastics, and rubber are more difficult to identify, but this is not a serious deficiency because the markets for these products are limited if existing at all, and because their recovery from raw refuse under existing concepts is also infeasible except under the most unusual circumstances.

Several recent studies are important to the assessment of resource recovery under the proposed wet system concept. Darnay and Franklin[4] have published a comprehensive analysis of market conditions for materials potentially recoverable from municipal solid waste, and Drobny et al.,[5] and Hershaft[6] have analyzed the cost performance characteristics of unit processes and systems applicable to resource recovery from municipal solid waste. In each of the following sections, we shall briefly summarize the anticipated market conditions for the recovered product and the recovery technologies now existing or under development. These brief discussions set the framework for the analysis of recovery opportunities under the wet system concept.

As we shall discover, the proposed wet system has greater potential for energy recovery than for materials recycling under both present and forecasted market conditions. In a time of national energy shortage, this may prove to be as important a consideration as materials recycling. Moreover, the fuel shortages projected for the very near future threaten to have significant adverse impacts on all sectors of the economy, the balance of payments and national security, and thus any contribution to increasing domestic energy supplies, however small, should be carefully examined.

Glass

Salvage Market for Ground Waste Glass ("cullet"). There is no effective market for cullet through the dealer system,[7] and cullet is not presently recovered from raw municipal refuse. However, cullet is an essential input material to most glassmaking processes, and average cullet utilization for glass containers may be 15 percent by weight. But manufacturers prefer to use their own, internally generated cullet because they have no question about its quality and chemical composition, and purchased cullet consumption presently constitutes only 1 percent of the raw materials in the glass container segment of the industry.[8]

The basic raw materials for glassmaking (sand, soda ash, and limestone) are low in cost and readily available. Raw materials costs average \$16 to \$20 per ton for glass containers, with sand costing about \$5 to \$5.50 per ton delivered. Some industry experts say that cullet use saves the plant \$2 to \$3 per ton of input because it produces a faster melt and reduces fuel consumption and furnace deterioration. If so, cullet can sell from \$18 to \$23 per ton and be competitive with virgin materials.[9]

Darnay and Franklin concluded in their analysis of the market for cullet that while 20 to 40 percent of the glass content of refuse could be used for recycling in glass container manufacture, the low cost of virgin materials, for which no shortage can be foreseen, makes cullet recovery feasible only as part of a comprehensive waste processing system.

Another potential market may one day exist for crushed waste glass as an aggregate in "glasphalt," a product under development at the University of Missouri, in which glass substitutes for crushed limestone in asphalt for paving streets.[10] The U. S. Bureau of Mines is also experimenting in building bricks made from waste glass recovered from incinerator residues.[11] Both of these applications are still in the experimental stages, but could one day become important.

Recovery Technology. One of the major requirements for recycling of cullet is a separation by color. An optical separation system developed by the Sortex Company is now being tested for sorting of glass from municipal refuse. A stream of glass particles is dropped through an optical box in which there are three photocell assemblies set at 120° intervals, and suitable illumination sources. Opposite each photocell head is a background with variable shades of color. Each particle passes through the viewing area and if there is a change in its reflectivity with respect to the background standard, either lighter or darker as desired, a blast of compressed air is triggered to deflect the off-color particle from the main stream.[12] One of the difficulties with this system is the limitation on particle size; the system works best at sizes of 0.25-0.75 inches. It is planned to install this system at the Black-Clawson demonstration plant in Franklin, Ohio, described elsewhere in this Chapter.

High intensity magnetic separators can also separate colored from colorless glass, and such a method is used by the Bureau of Mines system for resource recovery from incinerator residues.[13]

Implications for the Wet System Concept. Under the proposed system, glass would be ground in the individual home, transported in the sewer system to the treatment plant, and collected in the grit chamber. Washing of the grit in a grit washer would produce a grit free of organic matter and consisting of at least 95 percent by weight of glass and nonferrous materials. This raw material is not unlike that produced by the hydrocyclone of the Black-Clawson system, and would therefore be amenable to the same recovery processes if these are successfully proven. It is possible that the size of the ground glass might be smaller due to abrasion during hydraulic transport, and this would make optical sorting more difficult. However, Darnay and Franklin's analysis of market conditions indicates that the raw material from the grit washer would probably not be worth processing for glass cullet unless other recovery operations also occurred at the treatment plant. The most probable fate of the grit produced at a treatment plant is as coarse fill material. As noted previously, one can expect about 40 cu ft per million gallons;[14] thus a 100 mgd plant would produce 1,040 cu yds per week. This glass grit might be of a fairly uniform particle size distribution, and suitable as fill for construction purposes, or in the glasphalt and bricks described above.

The Beverage Container Problem. Reduction of the glass content in residential refuse is of course an alternative approach to attemps at recovery from a mixed waste, and there has been much recent interest in the imposition of legislative incentives to control glass and metal beverage containers. These incentives, imposed at the state and local level, take the form of mandatory deposits on containers, or taxes or complete bans on beverages sold in no deposit-no return containers.

A recent comprehensive study[15] concluded that beverage containers constituted 20 percent of items littered, but only 4 percent by weight of residential refuse, and consequently even effective incentives would have only a small impact on solid waste collection and disposal costs. However, beverage containers represent a much higher proportion of the nongrindable items in residential refuse, constituting about 25 percent by weight of the metal and glass fraction. Any significant reduction in the glass content of refuse would reduce the deposition problems in the sewer system, and any reduction in the metal content would reduce the problem of storing nongrindable metals. Consequently, it can be concluded that successful legislation in this area would have a greater beneficial impact on the wet systems approach to residential solid waste management than on existing practice.

Nonferrous Metals

Aluminum is the most abundant nonferrous metal occurring in residential refuse, and its porportion has increased in recent years as its use in container and packaging material in cans, foils, trays and the like, has become more widespread. As shown on Table 9, aluminum constitutes about 0.8 percent of residential refuse.

The Salvage Market for Secondary Aluminum. Economics favor secondary recycled aluminum because the production of primary aluminum requires high capital investments of $700-$800 per ton of annual capacity and large amounts of electric power, in the order of 15,000-16,000 kwh per ton of aluminum. Consequently, such smelters tend to locate near sources of low cost electricity; but these are usually remote from industrial centers, and therefore primary aluminum producers have high freight costs, ranging from $5 to $30 per ton. Primary aluminum production costs, including freight to fabricators, range from $306 to $470 per ton.[16] In contrast, secondary smelters can install capacity for $100-$120 per ton and can locate near scrap sources that are nearer the points of consumption, which in turn means lower freight costs. Operation costs are also cheaper because the major operation is scrap melting rather than electrolytic reduction of aluminum ores to aluminum. Secondary smelter total production costs range from $375 to $450 per ton.[17]

Recovery Technology. The Bureau of Mines has developed a process for the recovery of metals and glass from incinerator residues.[18] Two ferrous metal fractions and two nonferrous metal fractions are separated from the main stream by a series of electromagnets and screens. Aluminum is recovered from the nonferrous fractions by a so-called heavy media separator, in which the nonferrous metals are fed into a ferrosilicon-water slurry having a specific gravity of 2.95. Aluminum will float to the top of this slurry, whereas the copper-zinc fraction sinks to the bottom. The Bureau of Mines claims that the float product will contain about 96 percent aluminum, the bottom product 50 percent copper and 40 percent zinc.[19]

Table 9: Composition of Residential Refuse, 27 Routes in 4 SMSA's
January - March 1972

	Percent by Weight of Waste Collected				
	Buffalo, New York 8 Routes	Orlando, Florida 6 Routes	Cleveland, Ohio 7 Routes	Wichita Falls, Texas 6 Routes	Average
Food Waste	20.4	13.4	18.2	22.5	18.6
Paper	37.1	28.1	38.8	40.5	36.1
Newspaper & Magazines (Percent of Paper)	36.5	39.2	25.8	28.9	32.6
Garden Waste	0.4	28.1	4.8	4.9	9.55
Plastics	3.0	1.8	3.8	4.6	3.3
Rubber & Leather	1.8	2.9	0.5	0.2	1.35
Textiles	1.7	1.7	2.9	5.1	2.85
Wood	0.2	0.1	0.9	0.1	1.3
Metal	16.3	9.9	13.7	12.3	13.05
Aluminum (Percent of Metal)	1.9	15.7	1.6	6.2	6.35
Glass & Ceramics	18.2	11.6	14.3	8.2	13.07
Rock, Dirt & Ash	0.9	2.2	2.1	1.6	1.7

Source: "Data Acquisition and Analysis System Quarterly Report Jan.-Mar. 1972," ACT Systems Inc., Winter Park, Florida, April 1972, p. 42.

Implications for the Wet System Concept. Aluminum would be recovered in the grit chamber, and washed free of organics together with the other grit components in the grit washer. From this clean grit, aluminum might be recovered by the Bureau of Mines separation process described above. However, aluminum recovery would only be economically feasible in conjunction with glass recovery, as the amounts of aluminum could not be ground in household grinders, the probable percentage of aluminum recovered at the treatment plant would be less than the 0.8 percent indicated by Table 9, and probably no more than 0.4 percent. Thus, the maximum per capita yield is 0.004 x 1.8 lb/cap/day refuse (dry weight) = 0.007 lb/cap/day. A city of 250,000 would thus generate 1,750 lbs. of aluminum per day in the treatment plant grit. Aluminum scrap sells to dealers at between $150-300/ton, depending on the quality,[20] and thus assuming a recovery efficiency of 80 percent, the revenue of the aluminum recovered would be about $105 - 210/day.

There is some question as to whether the Bureau of Mines process would be economically suitable for glass and aluminum recovery alone. Copper and zinc, which are the most valuable of all non-ferrous metals recovered, find their way into municipal refuse by way of discarded electrical appliances; but these would not be ground in household grinders and therefore the copper and zinc content of the grit would probably be negligible.

Ferrous Metals

Ferrous metals constitute about 12 percent of residential refuse, consisting for the most part of steel cans. There are certain small markets for some of these cans, but generally the basic problem is an absence of demand for ferrous scrap from municipal refuse. However, where local circumstances do favor ferrous scrap recovery, the wet systems concept for refuse collection appears to have some definite advantages over existing solid waste management practice.

Salvage Market for Steel Cans. Although scrap steel is an essential input to modern steelmaking processes, supplies of desirable scrap exceed demand, the surplus being mainly in inventories of junk automobiles. Presently, only three forms of recovery from municipal refuse are generally practiced;[21] steel cans recovered from incinerator residues and sold to copper mines for so-called "precipitation iron,"[22] massive iron pieces and bulky materials also recovered from incinerator residues, and ferrous materials retrieved from dumps and landfills by scavengers. Darnay and Franklin[23] conclude that only the precipitation iron market readily accepts salvaged steel cans, but that even this market is already almost saturated. The problem of metal impurities in the ferrous scrap, such as tin and aluminum, and the abundance of other scrap supplies of a more homogeneous character, result in a complete absence of demand for ferrous scrap from refuse. Moreover, projections indicate that the future will bring no substantial changes to existing market conditions.

Implications for the Wet Systems Concept. Because the household grinder will be designed to reject ferrous metals in order to avoid deposition problems in the sewers and because the power requirements for grinding ferrous metals would be excessive, the nongrindable ferrous metals would be separated from the remaining fractions of refuse by the grinder, and dumped into a reject storage container at the end of the grinding cycle. These rejects would also contain ductile plastics and a few other resilient items, but would be free of paper and organic matter. In particular, the ferrous materials, such as tin cans, would be free of labels and paint. These nongrindables would be collected by periodic conventional collection, and it would seem that magnetic separation of the ferrous materials from the rejects would be a very cheap and simple operation if any local demand existed.

A major advantage of this procedure is that the separation of the ferrous metals is achieved mechanically, with no demand on the householder as the metals are inserted into the grinder together with the remaining refuse. Indeed, inserting metal cans into the grinder is preferable to manual separation in order to remove putrescible matter. Experience with household separation of refuse under existing solid waste management concepts has shown that initial success is generally followed by ultimate failure as householder enthusiasm tapers off. Darnay and Franklin report on several cities that initiated such programs.[24] For example, Los Angeles started a program for steel can recovery in 1961; cans were collected separately, and to ensure that segregation was accomplished, city inspectors examined garbage containers periodically. Any garbage containers found to contain cans were tagged and bypassed by the collection crews. Steel cans were picked up once every three weeks, and householders were thus required to wash them free of putrescible matter. But after initial success, the rapidly declining number of cans recovered forced abandonment of the program after 3 years.[25] The household refuse grinders thus have the advantage of separating and cleaning steel cans with no demands on the householder whatsoever. It is still questionable whether even the enhanced environmental awareness of recent years would sustain a household separation project that requires any significant effort on the part of the householder.

Source Reduction by Regulatory Measures. Just as beverage containers represent a major problem under existing solid waste management practices, so would ferrous metals be a major problem under the wet systems concept in that these represent the largest single category of nongrindables. It is not inconceivable therefore that similar regulatory approaches (see above, The Beverage Container Problem) to reduce the ferrous metal content in domestic refuse might be instituted if the wet systems concept were implemented. The replacement of steel by aluminum for beverage containers is already evident, and this trend might well be widened to include canned food containers.

Paper

Paper is the largest single component of residential refuse, and therefore, the idea of recovery is at first glance very attractive. Unfortunately, the realities of the salvage market for recycled paper, and the inherent barriers to reuse of waste fibers, make fiber recovery on a large scale highly questionable. This is not to say that individual fiber recovery projects from municipal refuse have not been successful, and we shall see that the wet systems concept could be successfully integrated with the most promising of these, the Black-Clawson process. However, for widespread application, the idea of paper fiber recovery remains questionable, regardless of whether the wet systems concept for refuse collection is implemented or not.

Salvage Market for Waste Paper from Municipal Refuse. The most important point to bear in mind in considering the potential for paper recycling is that already much more waste paper is available than consumed. Because the fibers lose length and strength every time they pass through the recovery-reuse cycle, there is a definite upper limit to the proportion of recycled fiber in most grades of paper. For the same reason, used fibers cannot be employed except in the same quality product or in a product of lower quality than the one in which they were first used. They cannot be employed in a higher quality paper or paperboard product.[26] Moreover, existing public health regulations impose severe constraints on fiber recycling; paperboard for food cartons, especially cartons for milk and other liquid foods, must be made of virgin fiber or clean, sanitary scrap from such paperboard. This is a severe limitation on possible fiber recovery via the wet systems concept that would bring the fibers in contact with sewage. However, this limitation appears more of an institutional than technical barrier, because processes have been developed by the paper industry that can effectively remove micro-organisms and contaminants from fibers.

All these limitations result in very low prices for wastepaper and the resultant secondary fibers. Not only are prices offered for wastepaper highly dependent on the proximity of potential consumers, but they exhibit fluctuations that make predictions for future market prices somewhat hazardous.[27] It should be noted that the Black-Clawson fiber recovery operation from municipal refuse in Franklin, Ohio, is dependent on a nearby captive market that uses the recovered fiber for roofing felt.

Recovery Technology. The most promising system for the recovery of fiber from municipal refuse is that developed by the Black-Clawson Company, a process now under demonstration at a 150 ton/day design capacity facility in Franklin, Ohio.[28] Raw refuse is conveyed into a pulper that converts pulpable material into a water slurry of 3-4 percent solids. The slurry containing paper, food waste and plastics, as well as glass, aluminum, small metal objects and similar material is extracted from the bottom of the pulper through 0.75-inch diameter openings. Large, heavy objects such as stones, pieces of metal, and tin cans are ejected through an opening near the bottom of the pulper, removed from the system by a continuous bucket elevator, and subsequently subjected to magnetic separation for recovery of ferrous constituents. The principal components of the process are shown schematically on Figure 15.

Slurry from the pulper is pumped through a hydro-cyclone to remove most of the inorganic content. Particles removed in this operation range in size from 0.75 inches down to fine sand. The washed rejects from the hydro-cyclone are about 80 percent glass, and they contain most of the aluminum that is introduced into the system; the slurry from the hydro-cyclone contains most of the paper, plus plastics, textiles and food waste. The next step is to reduce to discrete fibers any paper that may have passed through the 0.85-inch openings of the pulper as flakes, and to screen out all of the stringy materials and large pieces of plastic, twigs and leather.[29]

This operation is carried out in the specially designed defibering screen, which has a high-speed rotor operating against a heavy screen plate dotted with 0.125-inch perforations. The rotor is similar to the one employed in the pulper, but it is designed to defiber by shear rather than by cutting, and its pulsating action prevents the 0.125-inch screen plate from plugging up. A second stage of screening is performed in a conventional paper-mill pressure screen, which has a cylindrical screen basket with 0.0625-inch perforations. The screen surface is also kept clean by the pulsating action of a rotor that turns inside of the cylinder. This rotor is designed to provide pressure and suction pulses without shear. Objects larger than 0.0625 inches, and inflexible particles such as wood slivers are removed from the slurry in this operation.

The slurry is then subjected to a second stage of centrifugal cleaning, this time with high-efficiency cyclone cleaners having a 50 psi pressure drop. About 2,000 times the force of gravity is developed at design, and smaller slivers and fine dirt are removed in this operation. The last step in mechanical separation is to remove the very short fibers and debris, food particles, clay fillers and pigments, and similar materials from the long cellulose fibers of paper making quality. The slurry is pumped over an inclined screen with horizontal slots, with about 85 percent of the water going through the slots carrying fine particles with it. Long fibers pass over the surface of the screen, which has a slot width of 0.02 inches. Finally, the fibers are dewatered down to about 40 percent solids in a cone press. The rejects from the screens are dewatered, incinerated, and the waste stream from the fine screen dumped to the sewer. The marketability of the fiber is reduced because of contamination with greases, oils and micro-organisms that are present in higher than normal proportions. These would need to be removed by a conventional cooking step with caustic soda if the fibers were to be used in higher grade products.

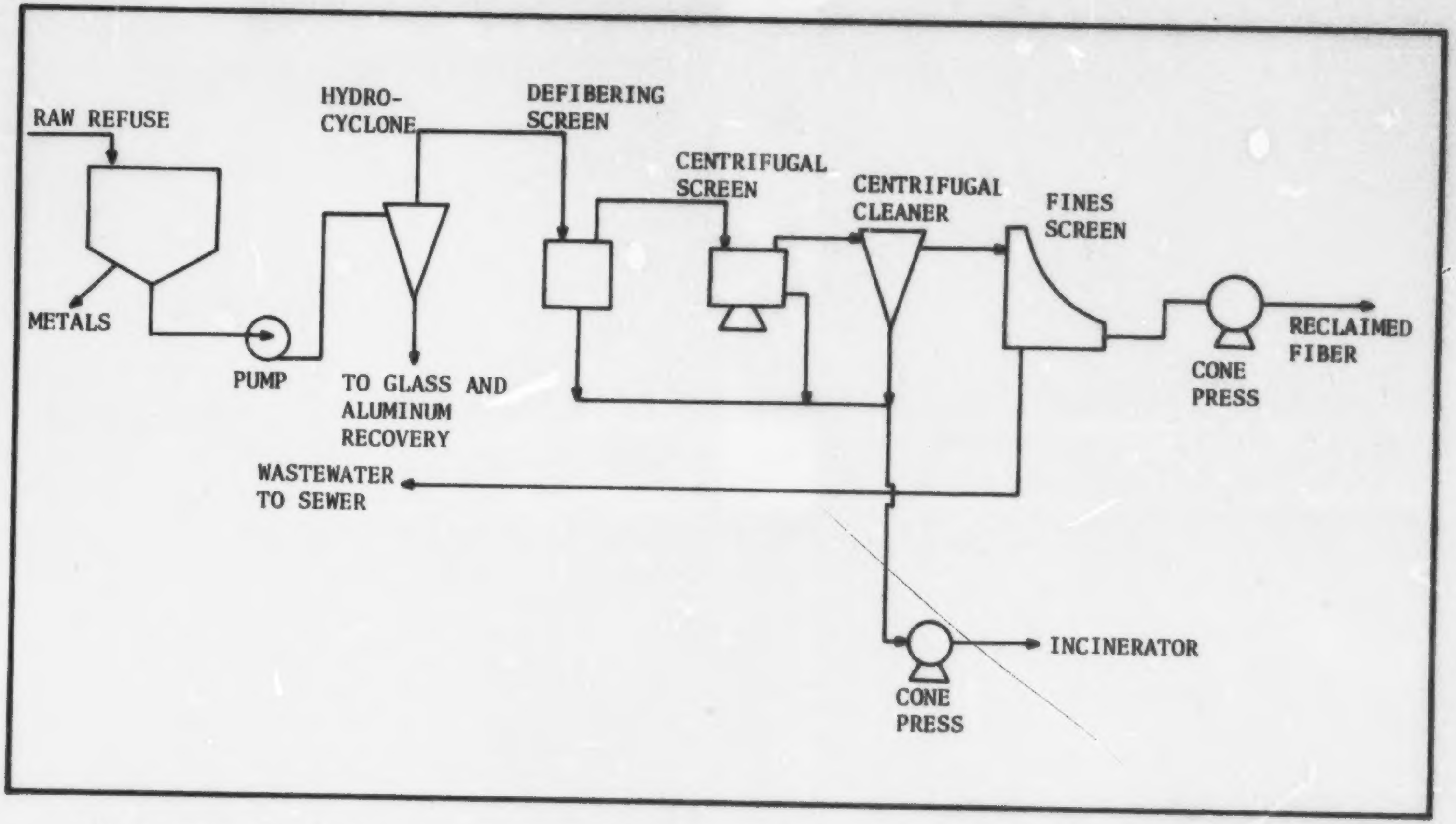
RAW REFUSE
METALS
PUMP
HYDRO-
CYCLONE
TO GLASS AND
ALUMINUM
RECOVERY
DEFIBERING
SCREEN
CENTRIFUGAL
SCREEN
CENTRIFUGAL
CLEANER
FINES
SCREEN
CONE
PRESS
RECLAIMED
FIBER
WASTEWATER
TO SEWER
CONE
PRESS
INCINERATOR

Figure 15: The Black-Clawson Process for Fiber Recovery (Source: Herbert, op. cit., p. 67).

Implications for the Wet Systems Concept. The effluent from the grit chamber at a treatment plant treating ground refuse and sewage corresponds to the hydro-cyclone effluent of the Black-Clawson process, being free of glass and metals. Were fiber recovery to be practiced at such a treatment plant, a screen such as the Bauer hydro-sieve discussed in Chapter IV would be inserted between the grit chamber and secondary treatment, a primary clarifier not being required in such a case. One possible arrangement is illustrated on Figure 16. Note that the screenings would be remixed with water to produce a slurry of about 3.5 percent solids, which is the concentration required by the fiber recovery screens of the Black-Clawson process. To what extent the operation of the fiber recovery process would be affected by the residence time of the ground refuse in the sewers is unknown, but no insurmountable technical difficulties are anticipated. Because the paper would probably be reduced to discrete fibers during sewer transport, the defibering screen might not be required and could be replaced by a simple coarse screen to remove the stringy material and large plastics.

But whether or not such a process would be an economic proposition is another matter, given the uncertainties of the reclaimed fiber market. Nevertheless, one may conclude that the wet systems concept for refuse collection is entirely compatible with the existing direction of technology development for fiber recovery. If a local market were to exist, then fiber recovery under the wet system concept would need to justify only the series of screens, because the pulping stage and the glass and metals separation of the Black-Clawson are required by the wet systems concept whether or not fiber recovery is practiced.

Heat Recovery

Steam Production at Incinerators. The recovery of waste heat from solid waste incinerators has long been considered as a way of offsetting costs and as a conservation measure. However, the sale of steam or power from such units that incorporate a waste heat boiler has been hindered by the difficulties of marketing and distribution to potential users. In the United States, waste heat recovery from municipal incineration is still the exception rather than the rule.[30] It is also generally held that such plants are troubled with excessive slagging, corrosion and boiler tube deposits. It is quite probable that sludge incinerators at plants treating ground refuse in sewage would also be faced with similar marketing problems were heat to be recovered, although particular local conditions might be favorable. Drobny *et al.*, report on several municipal incinerators that practice waste heat recovery, the largest of which is Chicago's Southwest Incinerator.[31] This facility produced 4,000 lbs. of steam per ton of refuse at a cost of $0.50 per 1,000 lbs., which is sold at $0.625 per 1,000 lbs. to a private contractor.

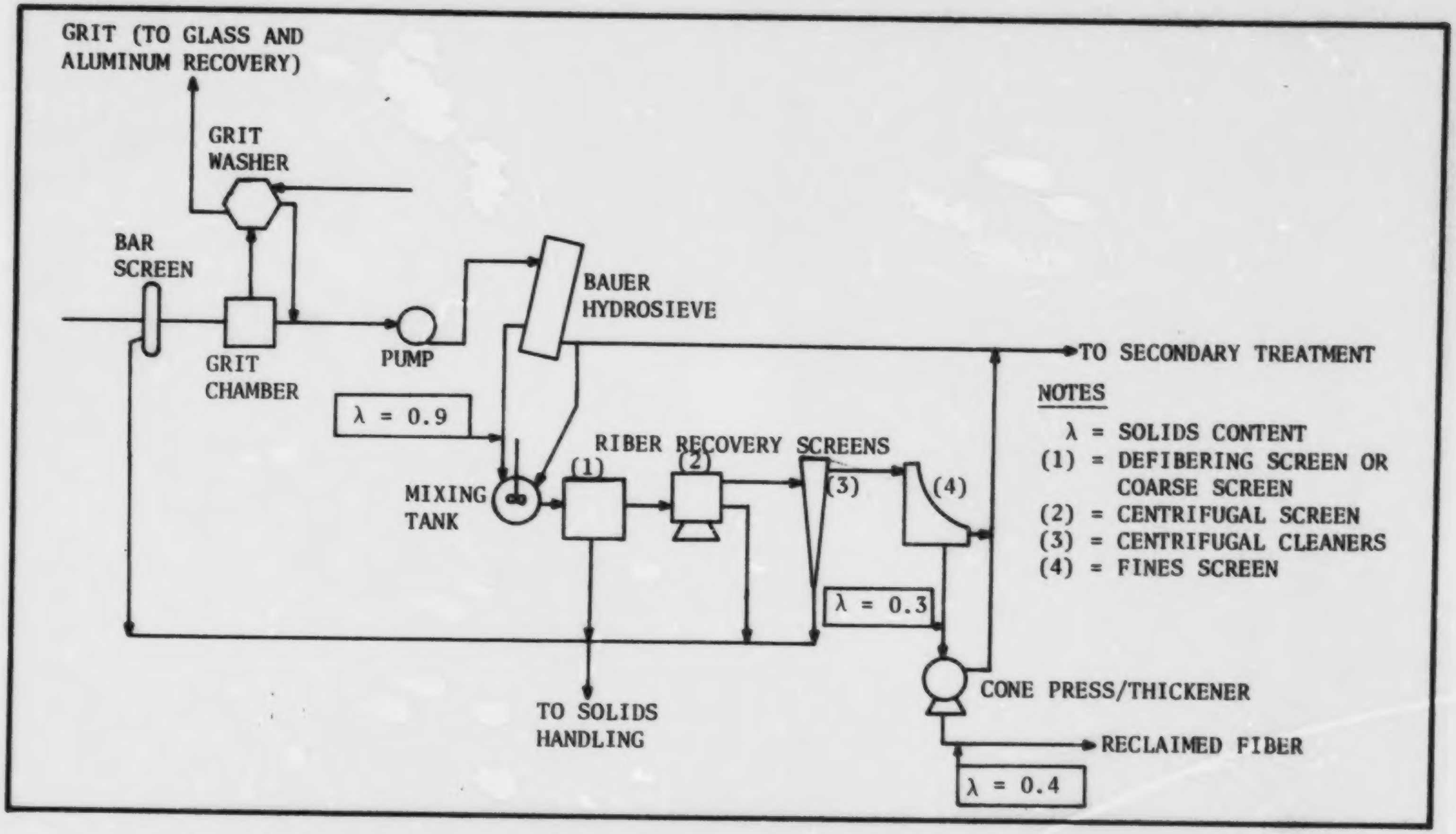
GRIT (TO GLASS AND ALUMINUM RECOVERY)
GRIT WASHER
BAR SCREEN
GRIT CHAMBER
PUMP
BAUER HYDROSIEVE
TO SECONDARY TREATMENT
λ = 0.9
MIXING TANK
RIBER RECOVERY SCREENS
(1)
(2)
(3)
(4)
λ = 0.3
CONE PRESS/THICKENER
TO SOLIDS HANDLING
RECLAIMED FIBER
λ = 0.4
NOTES
λ = SOLIDS CONTENT
(1) = DEFIBERING SCREEN OR COARSE SCREEN
(2) = CENTRIFUGAL SCREEN
(3) = CENTRIFUGAL CLEANERS
(4) = FINES SCREEN

Figure 16: Fiber Recovery at a Treatment Plant Treating Ground Refuse and Sewage

Sludge Cake as a Supplementary Fuel at Coal-Fired Power Facilities. One of the reasons for the lack of success with heat recovery from municipal refuse incinerators is their relative inefficiency, because they require high amounts of excess air in order to reduce slagging problems. However, power utility boilers that burn pulverized coal are very efficient with high furnace temperatures and low excess air requirements.[32] Moreover, an existing power plant is already integrated into a system for marketing and producing power, and it follows that if refuse could be burned in coal-fired power utility boilers without significant adverse effects, significant economies in the cost of both power production and refuse disposal could be realized.

The concept of replacing a modest percentage of coal by suitably prepared municipal refuse is now under full scale testing in St. Louis. The City of St. Louis, the Union Electric Company and the U. S. Bureau of Solid Waste Management, in cooperation with the National Air Pollution Control Administration, are collaborating in a $2.6 million demonstration project.[33] Some 30 percent of the refuse collected by city trucks, about 300 tons per day, will be fed to a 125 MW pulverized coal boiler unit on a 10 percent refuse - 90 percent coal basis. At this mixture, it is estimated that by 1983, the Union Electric Company could consume twice as much refuse as is generated in the entire St. Louis metropolitan area. Other cities are also reported as undertaking similar experiments with local power utilities.

If raw refuse is being considered as a supplementary fuel, why should we not also consider dried sludge cake as a fuel supplement? The quantities of sludge cake produced at a treatment plant treating ground refuse would be substantial and undigested sludge, suitably dried, has a heat value per pound equal to that of raw refuse. Possible advantages of burning sludge cake rather than raw refuse at coal fired utility boilers include a more homogeneous product, the absence of metal, glass and grit which would cause fewer abrasion problems than if raw refuse were burned[34] and the fact that no grinding and shredding equipment would be required at the power plant site.

Digester Gas

Although most who have researched the anaerobic digestion of refuse have concluded that the production of gas per pound of volatile solids decreases over the digestion of sewage solids alone, the significant increase in volatile solids makes possible a large yield of digester gas. Estimates discussed elsewhere ranged from 4000 cu ft to 6000 cu ft of methane per ton of raw refuse converted. Some of this gas could be used for preheating the feed to the digester, heating the digester itself and for mixing the digester, but Pfeffer has calculated that these would require less than 10 percent of the potential yield.[35] Consequently, there would be a significant surplus of gas at a facility where the ground refuse sludges are digested, far greater than the small amounts of excess gas at existing sewage sludge digesters that are not worth recovery and are therefore burnt. On a per capita basis, the increase is from 0.8 cu ft/cap/day typical at sewage digesters[36] to 3.0 cu ft/cap/day if ground refuse is also digested.

The Market for Digester Gas. The gas produced by refuse digestion contains 60-70 percent methane.[37] This is also a major constituent of natural gas, a fuel that is in critically short supply in many areas of the country. These shortages have increased the price of gas to a level such that it is economical to import liquified natural gas (LNG) from other parts of the world. A projection of the needs for natural gas in the U. S. is shown on Figure 17 from which it is clear that natural gas shortages can be expected in the very near future.[38]

In past years, sewage treatment plants contemplating the sale of surplus digester gas have been faced with sale prices of about 10 cents per 1000 cu ft (or about 20 cents per 1000 cu ft of methane). However, in the past two years, natural gas prices have risen dramatically; as early as June 1972 the Federal Power Commission authorized importation of LNG to terminals in Maryland and Georgia at prices of $0.77 and $0.83 per 1000 cu ft, and many anticipate prices of $1.00 per 1000 cu ft in the very near future.[39] At a price level, of, say, $0.80 per 1000 cu ft, and a conservative estimate of methane production of 7 cu ft per pound of volatile solids destroyed,[40] one may compute a dollar benefit per ton of sludge solids as

$$0.80 \times 10^{-3} \left[\frac{\$}{\text{cu ft}}\right] \times 7 \left[\frac{\text{cu ft}}{\text{lb VS}}\right] \times 0.8 \left[\frac{\text{lb VS}}{\text{lb}}\right] \times 2000 \left[\frac{\text{lb}}{\text{ton}}\right] = 8.96 \left[\frac{\$}{\text{ton}}\right] \qquad [5]$$

and a benefit per ton of raw refuse as

$$8.96 \left[\frac{\$}{\begin{matrix}\text{ton sludge}\\ \text{solids}\end{matrix}}\right] \times 0.61 \left[\frac{\text{lb sludge solids}}{\text{lb raw refuse}}\right] = 5.50\left[\frac{\$}{\text{ton refuse}}\right] \qquad [6]$$

A recent study for the Commonwealth of Massachusetts[41] estimated that digestion of refuse (including commercial and industrial) could cover about 25 percent of the existing gas requirements of the natural gas distributors in the state. The value of recovered methane was estimated at $9.50 per ton of refuse, whereas methane production costs were estimated at $1.80 to $3.00 per ton of refuse. Twenty-five percent of the total gas requirements is of course substantial and would therefore significantly affect any supply-demand determination of price in a static situation. But demand for natural gas is rising very fast (as evidenced by Figure 17), and the additional supply might therefore be absorbed with little change in price level. Indeed, the creation of an additional supply source might have the effect of restraining anticipated gas price increases (without actually depressing the price to levels at which recovery would be uneconomic). One may therefore

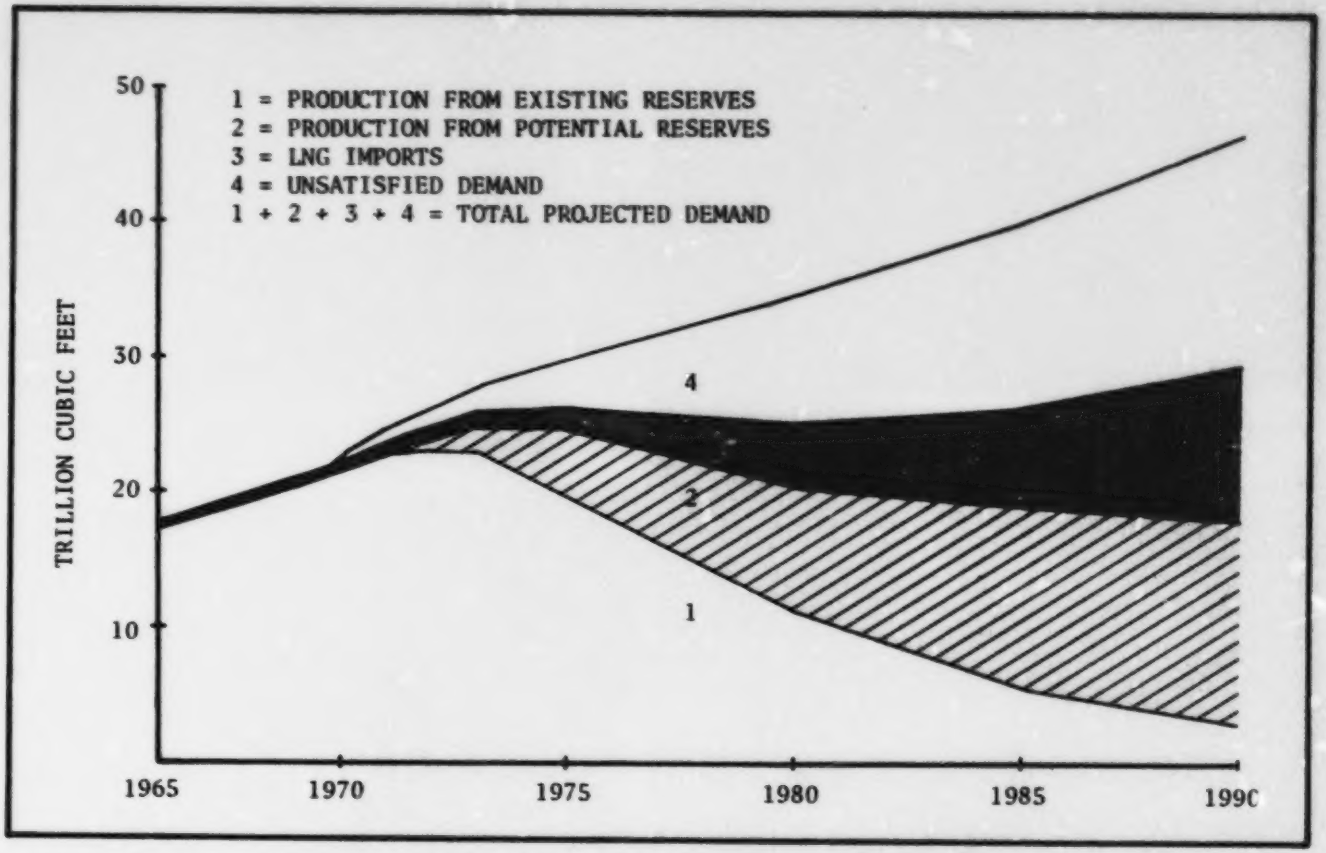

Figure 17: Projected Supply and Demand for Natural Gas in the U. S. (Source: National Gas Supply and Demand 1971-1990. Federal Power Commission Bureau of Natural Gas, 1972.)

conclude that in areas of natural gas shortage, such as New England, market conditions are highly favorable for methane production in digesters. Moreover, methane production would also have beneficial impacts on the balance of payments in that less imported liquified natural gas (LNG) would be required to meet the demand in excess of home-produced supplies.

Existing Uses for Digester Gas. Digester gas produced at existing sewage treatment plants is used for a variety of purposes at the treatment plant itself, including heating of buildings, heating of the digester feed and the digesters themselves, drying and incineration of sludge, incineration of screenings and as a fuel for internal combustion engines to drive pumps, air compressors and generators.[42] Many treatment plants are completely self-sufficient with respect to fuel requirements for light and power, effecting some substantial savings in operating costs. A potential problem frequently encountered is the presence of hydrogen sulfide, which is rapidly corrosive to gas engines in the presence of moisture. However, both wet and dry type scrubbers are successfully employed to remove this gas prior to use.

The Potential for Electric Power Production. Given that a ton of raw refuse will yield no less than 4000 cu ft of methane, a heat to energy conversion efficiency of 0.25,[43] a heat value of 1000 btu/cu ft, and an equivalence of 3416 btu per kilowatt hour (kwh), then the electric energy yield per ton is given by

$$4000 \left[\frac{\text{cu ft}}{\text{ton}}\right] \times 1000 \left[\frac{\text{btu}}{\text{cu ft}}\right] \times \frac{0.25}{3416} \left[\frac{\text{kwh}}{\text{btu}}\right] = 293 \left[\frac{\text{kwh}}{\text{ton}}\right] \qquad [7]$$

Thus a city of 250,000 inhabitants could generate energy at a rate of

$$250{,}000 \times 2.25 \left[\frac{\text{lb}}{\text{day}}\right] \times \frac{1}{2000} \left[\frac{\text{ton}}{\text{lb}}\right] \times 293 \left[\frac{\text{kwh}}{\text{ton}}\right] = 82{,}405 \left[\frac{\text{kwh}}{\text{day}}\right] \qquad [8]$$

or 0.3 kwh per capita per day.

This potential for power could be exploited in several ways. The most obvious is to burn the digester gas in gas turbines during the few hours of peak demand, thus producing high-value peak power. Gas turbines require the lowest capital investment per unit of capacity, and are ideally suited to peak load generation. They are not used for base load generation because their fuel costs are normally very high. The above calculation indicates that the gas would suffice to fuel a 20 MW gas turbine-generator unit 3-4 hours/day. Gas turbine generators used in the electric utility industry are now built in unit sizes of 20-80 MW,[44] so there would be no penalties of scale. But a potential obstacle to this idea is the possibility of corrosion problems due to to impurities in the digester gas, especially hydrogen sulfide.

Since a typical monthly use per household is about 500 kwh,[45] 0.3 kwh per capita per day is equivalent to

$$0.3 \left[\frac{\text{kwh}}{\text{cap/day}}\right] \times 30 \left[\frac{\text{days}}{\text{month}}\right] \times 3.5 \left[\frac{\text{cap}}{\text{household}}\right] = 31.5 \left[\frac{\text{kwh}}{\text{household/month}}\right] \qquad [9]$$

or about 6 percent of the total residential consumption. In New England, where average residential use is about 350 kwh per month, the power recovered from residential refuse would cover about 9 percent. Although this percentage is not that large, it would nevertheless make a substantial contribution to the total supply picture.

Whether or not there is a market for this power would depend on local conditions. Private utilities may be reluctant to see municipalities enter the field of power production, whatever the price offered. On the other hand, where a municipal utility already exists, that normally must buy its power from private producers, the possibility of generating its own peak power at a virtually zero fuel cost is clearly a very attractive proposition.

That the potential for power production is not academic is demonstrated by the Orange County Sanitation District in California, which built a digester gas turbine as early as 1966.[46] The district produced 2.3 million cu ft of digester gas per day, most of which was previously wasted. The arrangement of the installation is shown on Figure 18. Although the unit is very small (1 MW), and intended primarily as a source of stand-by energy during public power outages, the technical feasibility of the concept has nevertheless been demonstrated.

Conclusion. Regardless of whether the digester gas is sold to gas suppliers or whether the municipality generates its own power, the almost unlimited markets for gas and power, and the very low transportation costs required to bring the product to market, makes the utilization of digester gas the most attractive of all resource recovery options under the wet systems concept. Even if every treatment plant in the country were to produce digester gas from refuse, there would be little impact on price in view of ever-increasing energy demands. This is not the case for paper recovery where the potential markets would be swamped to the point of depressing prices to levels at which recovery would be quite uneconomic.

Other Potential Opportunities

Composting. A recent study has demonstrated the feasibility of composting dewatered sewage sludge to produce a compost with a 2 percent nitrogen and a 2 percent phosphorus content that worked well as a soil conditioner and was found to be free of indicator pathogens.[47] It is probable that the process would work also on a sludge that contains refuse solids as well as sewage solids. However, the market for compost

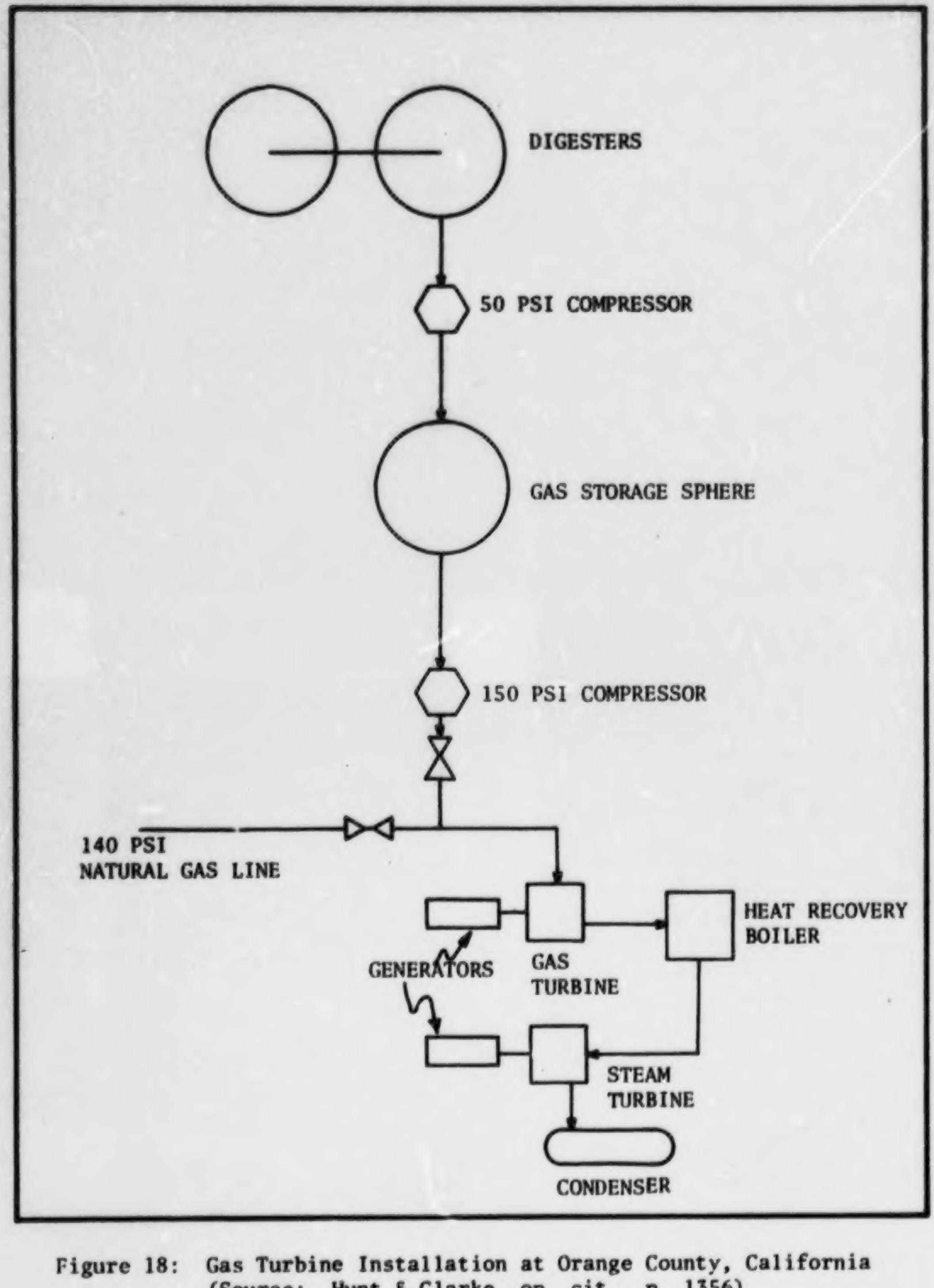
DIGESTERS
50 PSI COMPRESSOR
GAS STORAGE SPHERE
150 PSI COMPRESSOR
140 PSI
NATURAL GAS LINE
GENERATORS
GAS
TURBINE
HEAT RECOVERY
BOILER
STEAM
TURBINE
CONDENSER

Figure 18: Gas Turbine Installation at Orange County, California
(Source: Hunt & Clarke, *op. cit.*, p. 1356)

is almost nonexistent in the United States,[48] and it is extremely doubtful that market conditions will approach those presently existing in Europe where composting of refuse is widely practiced. The use of composting as a component of the wet systems concept for refuse collection is therefore highly questionable.

Pyrolysis. Pyrolysis, or destructive distillation, is a time-tested process for breaking down organic substances into a series of volatile oils and gases by heating at 600°C-1,000°C in the absence of air.[49] Renewed interest in using this process for converting municipal refuse into useful compounds has surfaced in the last few years, and several EPA Demonstration Grants are currently under way.[50] A typical product mix from the pyrolysis of one ton of municipal refuse would be 154-230 lbs. of char with a heat value of 8,000-13,000 btu/lb, 0.5-5 gallons of tar and pitch, 1.5-2 gallons of light oil, 110-130 gallons of organic acids and alcohols, 18-25 lbs of ammonium sulfate and 11,000-18,000 cu ft of gas with a heat value of 500 btu/cu ft.[51] Although several commercial enterprises have attempted to market pyrolysis systems, none have been built at major municipal systems to date.[52] The use of pyrolysis on a sludge consisting of a mixture of sewage and refuse solids does not yet appear to have been explored.

Conversion of Cellulose to Oil. The Bureau of Mines is currently experimenting with one type of pyrolysis process that converts all types of organic solid wastes, including sewage sludge and urban refuse, to a low-sulfur oil by reaction with carbon monoxide and water at pressures of 4,000 psi in the presence of various catalysts and solvents.[53] Cellulose conversions of 90 percent and better are claimed, and a continuous reactor has been successfully developed. Although this process appears compatible with the wet systems concept, the economics of the process are as yet undetermined.

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40. Kos, P., P. M. Meier and J. M. Joyce, "Economic Analysis of the Processing and Disposal of Refuse Sludges," Report by Curran Associates, Inc. to EPA Solid Waste Research Laboratories, Cincinnati, Ohio, March 1974.

41. "Study of Solid Waste Disposal for the Commonwealth of Massachusetts," Vol. III, Report by the Raytheon Service Company to the Massachusetts Department of Public Works, May 1972.

42. See e.g., WPCF, *Manual of Practice*, No. 8, p. 238-239.

43. See e.g., "Peaking Electric Power in New England: Future Demand, Supply and Environmental Impact," New England River Basins Commission, Nov. 1972, p. III-11. Future improvements in gas turbine technology are expected to raise thermal efficiency levels from the existing 25-30 percent to nearly 40 percent.

44. See e.g., Environmental Statement, Gas Turbine Peaking Plant Additions, Colbert Steam Plant, Alabama, TVA, March 31, 1972.

45. See e.g., "A Study of the Electric Power Situation in New England, 1970-1990." New England Regional Commission, Sept. 1970, Table 5-2. The average monthly use per residential connection in the United States is 500 kwh.

46. Hunt, H., and W. N. Clarke, "Design and Operation of the First Digester Gas Turbine in the USA," *J. WPCF*, Vol. 40, 7, p. 1346.

47. Shell, G. and J. Boyd, "Composting Dewatered Sewage Sludge," USPHS, Bureau of Solid Waste Management, Report SW-12c, 1969, (Contract 86-67-103).

48. "Composting of Municipal Solid Wastes in the U. S.," EPA Solid Waste Management Series Report SW-47R, 1971.

49. See e.g., W. Sanner, *et al.*, "Conversion of Municipal and Industrial Refuse into *Useful* Materials by Pyrolysis," U. S. Bureau of Mines, Report of Investigations RI 7428, 1970.

50. e.g., Office of Solid Waste Management Program Demonstration Grant 801-588 (to Garrett Research in San Diego, California), Grant 801-533 (to the Monsanto Corp., Baltimore, Maryland) and Grant 801-569 (to the Hercules Company, Wilmington, Delaware).

51. Sanner, *et al*., *op*. *cit*., p. 6.

52. Herschaft, *op*. *cit*., p. 33.

53. Appell, H. R., *et al*., "Converting Organic Wastes to Oil," U. S. Bureau of Mines, Report of Investigations RI 7560, 1972.

CHAPTER VI

ECONOMIC ANALYSIS

Introduction

The purpose of this preliminary economic analysis is to establish the range of costs anticipated for each of the most promising wet system alternatives, and to compare this range with the costs of existing solid waste management practices so as to make a preliminary assessment of economic feasibility. It should be noted that this economic analysis does not concern itself with detailed optimizations of the major system components; indeed, it cannot do so in the absence of case studies. The detailed systems analysis and the case study are tasks foreseen for Phase II of the project, and we thus make no claim to having established, for example, the optimum configuration of treatment processes. It is the order of magnitude of costs that are herein determined, not their breakdown for any particular application.

This analysis will establish two sets of comparisons - one for existing conditions (1973) and one for future conditions as projected for 1988, that is, fifteen years hence. The 1988 cost comparisons are expressed in 1973 dollars, thus avoiding the problem of making forecasts for inflation. Unless otherwise noted, we have assumed that labor costs will rise faster than other sectors of the economy, and labor costs for 1988 are derived on the basis of a 2 percent per year increase over existing levels (i. e. 2 percent in excess of inflation). Fuel and land costs are other items whose costs will probably rise at a faster rate than other sectors of the economy, but they represent a small fraction of total system costs, and are so dependent on local conditions that we have not made adjustments for them. While these assumptions may be simplistic, the resulting future cost comparison will reflect the differences in labor intensity, and hence in labor costs, between conventional and the wet system concepts.

The justification for the higher labor cost increase is primarily that of unionization. In fact, whenever unionization of a sanitation worker labor force does occur, the percentage increase will very likely be much higher than 2 percent; this figure thus represents a nationwide and time average rather than attempting to describe any particular situation.

Cost of Residential Refuse Collection

Analysis of Residential Collection Costs. There are two obvious methods of estimating the collection costs of nongrindables. The first is to derive the costs in terms of the performance of the collection process and estimates of labor and equipment rates; a typical approach would be to derive man-minutes per trip from pick-up time, disposal time, average haul speed, off-route time, etc., and subsequently compute total labor costs from total trip and man-minute requirements.[1] However, this procedure requires detailed analysis of the operational details that would tend to obscure the major relationships between wet system and conventional collection, and would in any case require some analysis on a case study to determine what operational changes would in fact be needed.

The second approach would utilize multiple regression techniques for evaluating costs as a function of various operational characteristics.[2] Although appealing in their approach, these multivariate models have the disadvantage that their sample bases are completely oriented to today's performances, so that the range of prediction needed for this study falls far beyond their statistical data base. Nevertheless, some preliminary multivariate analyses were conducted using data available from the Data Acquisition and Analysis Program of the EPA Solid Waste Management Office for 32 routes in 9 SMSA's in the months of January, February and March, 1973.[3] The results were inconclusive, with much of the total variance of per household collection cost explained by geographical location alone. It was decided to defer a more comprehensive analysis to Phase II, by which time the additional data would be available to allow detailed time series and cross-section analyses.

For the purpose of this preliminary analysis, therefore, a third approach was explored. This approach is based on the premise that the present cost of collection is based on a few important operational variables, and that the cost of collection of just the nongrindables may be related to the present cost by examining the relative changes in these variables. The most drastic change will occur in the frequency of collection, and we turn next to an analysis of this variable under the new conditions of a wet system implementation.

Frequency of Collection of Nongrindables. Because all putrescible matter in refuse is ground, and the nongrindables such as tin cans washed free of putrescibles, there are no limits to the length of time nongrindables could be stored prior to collection. Consequently, one may reason that the frequency of collection of nongrindables is determined only by the available storage space and the rate of use of that space. Under this assumption the frequency of collection of nongrindables, f_{NG}, is given by

$$f_{NG} = f_0 \cdot \frac{v_{NG}}{v_0} = \left[\frac{\text{freq}}{\text{week}}\right] \cdot \frac{\left[\frac{\text{vol}}{\text{week}}\right]}{\left[\frac{\text{vol}}{\text{week}}\right]} = \left[\frac{\text{freq}}{\text{week}}\right] \qquad [10]$$

where v_{NG} is the volume of nongrindables, and v_0 the volume of total refuse generated per week, and f_0 the frequency of collection required for collection of all refuse. For example, if $f_0 = 1$ and the volume of nongrindables is 10 percent of the total, then $f_{NG} = 0.1$, i.e. nongrindables are collected once every 10 weeks. A calculation of the volume reduction that can be expected is shown on Table 10, and under typical conditions the volume might be reduced from 0.246 cubic yards/Household/Week (cu yds/HH/W) to 0.043 cu yds/HH/W. Inserting these figures in Equation (10) and assuming $f_0 = 1$, yields $f_{NG} = 0.17$ or a collection about once every 5-6 weeks.

The computations shown on Table 10 assume that the bulk density of the nongrindable refuse components remains unaltered by the grinding process. However, grinding tests run by Foster-Miller show that significant compaction does indeed take place during grinding; steel cans, for example, emerge as crumpled lumps. Although quantitative estimates of this compaction during grinding are unavailable, it is reasonable to assume that the volume of nongrindables will be substantially less than that indicated by the calculations of Table 10. Thus one may write

$$f_{NG} = f_0 \frac{v^*_{NG}}{v_0} \qquad [11]$$

$$v^*_{NG} = v_{NG}\, \mu \qquad [12]$$

where μ is a compaction factor whose upper bound is 1 and whose lower bound may be around 0.3. The subsequent computations of this section make the assumption of $\mu = 0.5$; this also implies a bulk density considerably higher than that shown on Table 10 (which would increase to 214 x 1/0.5 = 428 lb/cu.yd). Thus the reason for a higher bulk density of nongrindables is compaction during grinding rather than the high bulk density of the materials that constitute the nongrindables. For example, metal in refuse, being mainly in the form of tin cans, has a lower bulk density than garbage, or wood, as indicated on Table 10.

Equations [11] and [12] assume that the volume of storage space for nongrindables is a constant equal to the storage space available under existing conditions for all refuse. However, there may be a substantial economic incentive for a householder to increase this storage space, and thereby further reduce collection frequency and costs. If the factor accounting for an increase in storage volume is denoted by π, then clearly

$$f_{NG} = f_0 \cdot \frac{v_{NG}\, \mu}{v_0\, \pi} \qquad [13]$$

We shall refer to π as the storage multiplier.

A Cost Function for Refuse Collection. In order to determine the cost function for the collection of nongrindables, it is first necessary to establish the existing annual per household cost. Analysis of the EPA

Table 10: Estimation of the Volume of Nongrindable Refuse

	X_i Percent By weight (See Table 9, Chapter V)	Y_i Percent Ground (Assumed values for a Foster-Miller type Grinder[4]	Z_i Bulk Density of Uncompacted Refuse, lb/cu.yd.
Paper	36.0	100.	120.
Garbage	18.0	100.	167.
Glass	13.0	90.	700.
Garden Wastes	9.5	90.	135.
Wood	1.3	90.	300.
Plastic	3.0	90.	80.
Rubber, Leather and Textiles	4.0	80.	400.
Metal	13.0	15.	160.
Other	2.2	50.	150.

Bulk density of raw refuse, $\rho = \sum_{i=1}^{n} \frac{x_i z_i}{100.} = 223.5$ lb/cu.yd.

Weight fraction ground, $g = \sum_{i=1}^{n} \frac{x_i y_i}{(100)(100)} = 0.83$

Volume of Raw Refuse per week per household

$$= 7\left[\frac{\text{days}}{\text{week}}\right] \times 2.25\left[\frac{\text{lb.}}{\text{cap. day}}\right] \times 3.5\left[\frac{\text{cap}}{\text{HH}}\right] \times \frac{1}{\rho}\left[\frac{\text{cu.yd}}{\text{lb}}\right] = 0.246\left[\frac{\text{cu.yd.}}{\text{HH.week}}\right]$$

Bulk Density of Nongrindables,

$$\rho_{NG} = \frac{\sum_{i=1}^{n} \frac{(100 - y_i) \cdot z_i \cdot x_i}{100}}{\sum_{i=1}^{n} \frac{100 - y_i}{100} x_i} = 214\left[\frac{\text{lb.}}{\text{cu.yd.}}\right]$$

Volume of Nongrindables per week per household

$$= 7\left[\frac{\text{days}}{\text{week}}\right] \times 2.25 \times (1 - g)\left[\frac{\text{lb.}}{\text{cap.day}}\right] \times 3.5\left[\frac{\text{cap}}{\text{HH}}\right] \times \frac{1}{\rho_{NG}}\left[\frac{\text{cu.yd}}{\text{lb}}\right]$$

$$= 0.043\left[\frac{\text{cu.yd.}}{\text{HH week}}\right]$$

Data Acquisition and Analysis Program yielded a distribution of costs as shown on Figure 19. Ninety percent of the sample annual costs lie in the range of \$10-\$40 per year.[5]

With this range as a basic reference point, consider next the cost of operating one collection truck one day. Defining y as the number of households (pickups) that can be served per truck trip, z the minutes required for each household (i. e. for each pickup) and M_{TR} the minutes spent in travel to and from the disposal site, then the total time spent per truck trip is

$$y \, . \, z + M_{TR} = \left[\frac{\mathrm{HH}}{\mathrm{trip}}\right] \cdot \left[\frac{\mathrm{mins}}{\mathrm{HH}}\right] + \left[\frac{\mathrm{mins}}{\mathrm{trip}}\right] = \left[\frac{\mathrm{mins}}{\mathrm{trip}}\right] \qquad [14]$$

then assuming an 8-hour day, the number of trips per day per truck, n, is clearly given by the expression

$$n = \frac{60 \times 8 - M_R}{y \, . \, z + M_{TR}} = \frac{\left[\frac{\mathrm{mins}}{\mathrm{day}}\right]}{\left[\frac{\mathrm{mins}}{\mathrm{trip}}\right]} = \left[\frac{\mathrm{trips}}{\mathrm{day}}\right] \qquad [15]$$

Where M_R is the minutes spent in travel to the beginning of the collection route and spent in routine daily equipment maintenance. The number of households served per day, m, is thus given by

$$m = n \, . \, y = \left[\frac{\mathrm{trips}}{\mathrm{day}}\right] \cdot \left[\frac{\mathrm{HH}}{\mathrm{trip}}\right] = \left[\frac{\mathrm{HH}}{\mathrm{day}}\right] \qquad [16]$$

and hence the cost per household served by this truck, which clearly also equals the cost per pickup, γ, is given by

$$\gamma = \frac{\sigma}{m} = \frac{\sigma}{n \cdot y} = \frac{\left[\frac{\$}{\mathrm{day}}\right]}{\left[\frac{\mathrm{HH}}{\mathrm{day}}\right]} = \left[\frac{\$}{\mathrm{HH}}\right] \qquad [17]$$

where σ is the total daily cost of operation for one truck. Now if the frequency of collection per week is f, then the number of collections per year is 52f and hence the annual per household collection cost is

$$\gamma = \frac{52\sigma f}{m} = \frac{52\sigma f \, (yz + M_{TR})}{y \, (480 - M_R)} \qquad [18]$$

Also, the households served per truck trip, y, is readily seen to be equal to

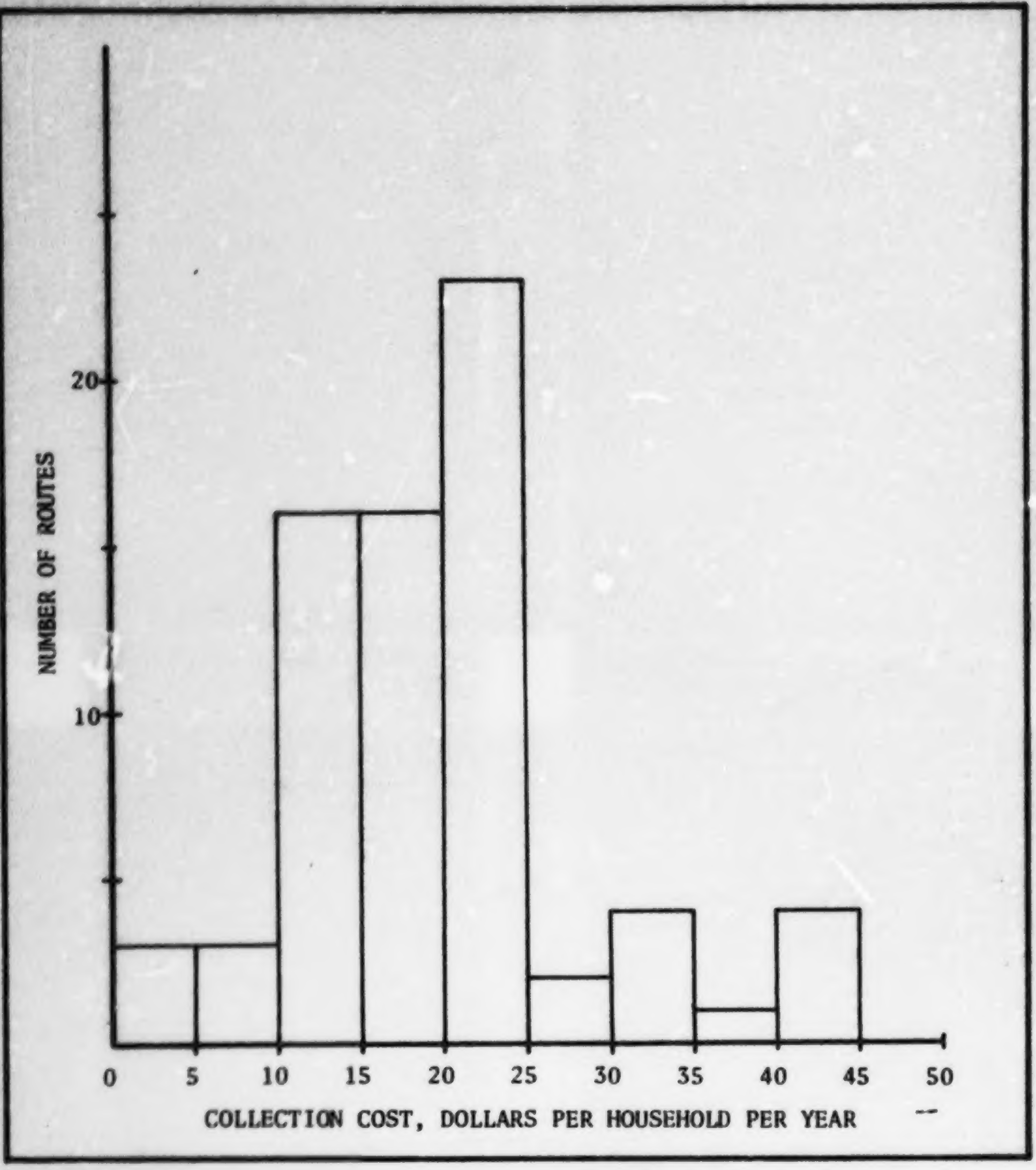


Figure 19: Histogram of Per Household Refuse Collection Costs

$$y = \frac{Q\,\overline{\rho}}{W} = \frac{\left[\frac{\text{cu yds}}{\text{truck trip}}\right]\cdot\left[\frac{\text{lbs}}{\text{cu.yd}}\right]}{\left[\frac{\text{lbs}}{\text{household}}\right]} = \left[\frac{\text{households}}{\text{truck trip}}\right] \qquad [19]$$

where Q = capacity of the truck in cubic yards, $\overline{\rho}$ is the compacted bulk density of the refuse and W is the pounds of refuse per household (per collection), which in turn is given by

$$W = \frac{r \cdot p \cdot 7}{f} = \frac{\left[\frac{\text{lb}}{\text{cap.day}}\right]\cdot\left[\frac{\text{days}}{\text{week}}\right]\cdot\left[\frac{\text{cap}}{\text{HH}}\right]}{\left[\frac{\text{freq}}{\text{week}}\right]} = \left[\frac{\text{lb}}{\text{HH}}\right] \qquad [20]$$

where r = refuse generation rate in lb/cap/day, and p = number of persons per household. Then substituting equation [19] into [18] one obtains

$$\gamma = \frac{52\sigma f\left[\frac{Q\,\overline{\rho}}{W}\;z + M_{TR}\right]}{\frac{Q\,\overline{\rho}}{W}\,(480 - M_R)} = \frac{52\sigma f\,(z + \frac{W}{Q\,\overline{\rho}}\;M_{TR})}{(480 - M_R)} \qquad [21]$$

It remains to define z, the collection time per household served, for which Clark[6] has derived the expression

$$z = 0.0679 + 0.0035\,W + 0.0010\,\phi + 0.0022\,\lambda \qquad [22]$$

where W = pounds of refuse collected per household, in our application given by Equation [20], ϕ is the number of households per mile and λ is the total collection time per day, in minutes.

Cost of Collection of Nongrindables. By subscripting Equations [21] and [22], using the subscript o for the collection of all refuse and the subscript NG for the collection of nongrindables, then the ratio of the cost of collection of nongrindables to the cost of collection of all refuse is given by

$$\frac{\gamma_{NG}}{\gamma_o} = \frac{\sigma_{NG}\;f_{NG}\left[Z_{NG} + \frac{W_{NG}M_{TRNG}}{Q\,\overline{\rho}_{NG}}\right](480 - M_{Ro})}{f_o\,\sigma_o\left[Z_o + \frac{W_oM_{TRo}}{Q\,\overline{\rho}_o}\right](480 - M_{RNG})} \qquad [23]$$

Because the existing cost of collection for all refuse, γ_o, will be known for any particular area, one may then multiply the right hand side of Equation [23] by γ_o to yield the cost of collection of just the nongrindables, γ_{NG}. If one assumes that the average travel time per day to the first collection route is unchanged, then $M_{Ro} = M_{RNG}$ and γ_{NG} is given by a rearrangement of the terms in Equation [23] as

$$\gamma_{NG} = \gamma_o \frac{\sigma_{NG}}{\sigma_o} \quad \frac{f_{NG}}{f_o} \left[\frac{Z_{NG} + \dfrac{W_{NG} M_{TRNG}}{Q\ \overline{\rho}_{NG}}}{Z_o + \dfrac{W_o M_{TRo}}{Q\ \overline{\rho}_o}} \right] \qquad [24]$$

Note that the weight of nongrindables, W_{NG}, is given by the expression

$$W_{NG} = W_o\ (1 - g) = \frac{r\ p\ 7}{f}\ (1 - g) \qquad [25]$$

where g is the weight fraction of refuse that is ground. Suppose that existing cost collection, γ^*, were \$25 per household per year, collected once per week, ($f^* = 1$) and with a per capita generation rate of $r^* = 2.25$ lb/cap/day. Then the ratio of the cost of collection of all refuse at a generation rate of W_o previously defined as γ_o, to the cost of existing collection, γ^*, may be obtained by appropriate subscription of Equation [21] to yield

$$\frac{\gamma_o}{\gamma^*} = \frac{\sigma_o\ f_o\ (z_o + \dfrac{W_o}{Q_o \overline{\rho}_o}\ M_{TRo})\quad (480 - M_R{}^*)}{\sigma^*\ f^*\ (z^* + \dfrac{W^*}{Q^*\ \overline{\rho}^*} M_{TR}{}^*)\quad (480 - M_{Ro})} \qquad [26]$$

If all parameters except the rate of generation remain unchanged, then clearly Equation [26] simplifies to

$$\gamma_o = \gamma^* \left[\frac{Z_o + \dfrac{W_o}{Q\overline{\rho}} M_{TR_o}}{Z^* + \dfrac{W^*}{Q\overline{\rho}} M_{TR}{}^*} \right] \qquad [27]$$

Figure 20 shows the dependence of γ_o and γ_{NG} as a function of r, the refuse generation rate, given existing conditions of $\gamma^* =$ \$25/Household/year, and $r^* = 2.25$ lb/cap/day. It is clear that under these assumptions the cost of collecting nongrindables will fall to about 5-10 percent of the existing costs. It is also of interest to note that in absolute terms, a doubling of generation rate from r = 2.25 to r = 4.5 would occasion a penalty of about \$4.50 per household per year for conventional collection of all refuse (or about 20 percent increase in cost), whereas the increase for collection of only the nongrindables is only \$0.25 or a 10 percent increase. Also, increasing the storage

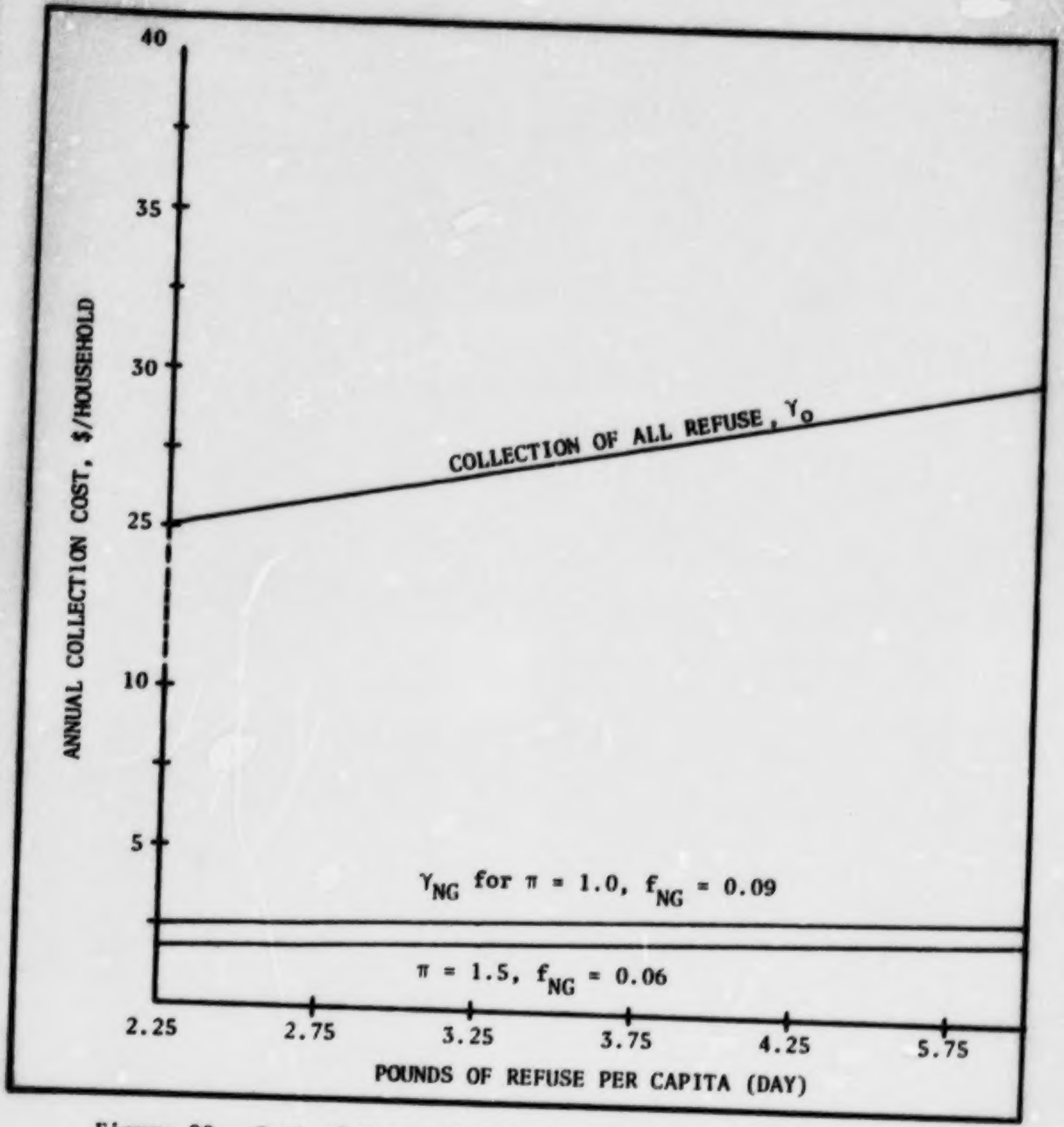


Figure 20: Cost of Collection of Nongrindables

by 50 percent brings only about a 20 percent decrease in cost. The explanation for this is that increased storage means larger amounts of refuse per collection, which in turn means fewer households served per truck trip and hence relatively higher transportation costs to and from the disposal site.

1988 Costs for Collection of Nongrindables. The 1988 costs are obtained by increasing that portion of existing costs due to labor, say β, by 2 percent per annum, as rationalized in the introduction. Then the 1988 cost of collection nongrindables, denoted γ_{NG} (1988), is given by

$$\gamma_{NG}\ (1988) = \gamma_{NG}\ (1973) \left[(1 - \beta) + \beta\ (1.02)^{15}\right] \qquad [28]$$

$$= \gamma_{NG}\ (1973)\ (1 + 0.34\beta) \qquad [29]$$

where γ_{NG} (1973) is the 1973 cost of collecting nongrindables, given by equation [24], and β is the labor fraction of total costs. Figure 21 shows the labor fractions β for the same collection routes as previously examined on Figure 19, with a mean of $\beta = 0.76$. Thus

$$\gamma_{NG}\ (1988) = 1.26\ \gamma_{NG}\ (1973) \qquad [30]$$

Also, by the same reasoning, the 1988 cost for collection of all refuse under existing practice, γ_0 (1988), is given by

$$\gamma_0\ (1988) = 1.26\ \gamma_0\ (1973) \qquad [31]$$

where γ_0 (1973) is the 1973 cost of collecting all municipal refuse as given by Equation [27]. Plots of Equations [30] and [31] are shown on Figure 22, for 1988 conditions corresponding exactly to those shown for 1973 on Figure 20.

Disposal Costs for Nongrindables

Because the nongrindables will consist mainly of ferrous metals, only two alternatives for their disposal need be considered, namely landfilling or resource recovery. Incineration would not be considered due to the lack of combustible components in the nongrindables. Landfilling might be feasible even in urban areas that are already experiencing difficulties in finding sites because of the much lower land requirements. If only 5 percent of total refuse is nongrindable, then land requirements for the nongrindables would be 20 times less than today (assuming equivalent compaction).

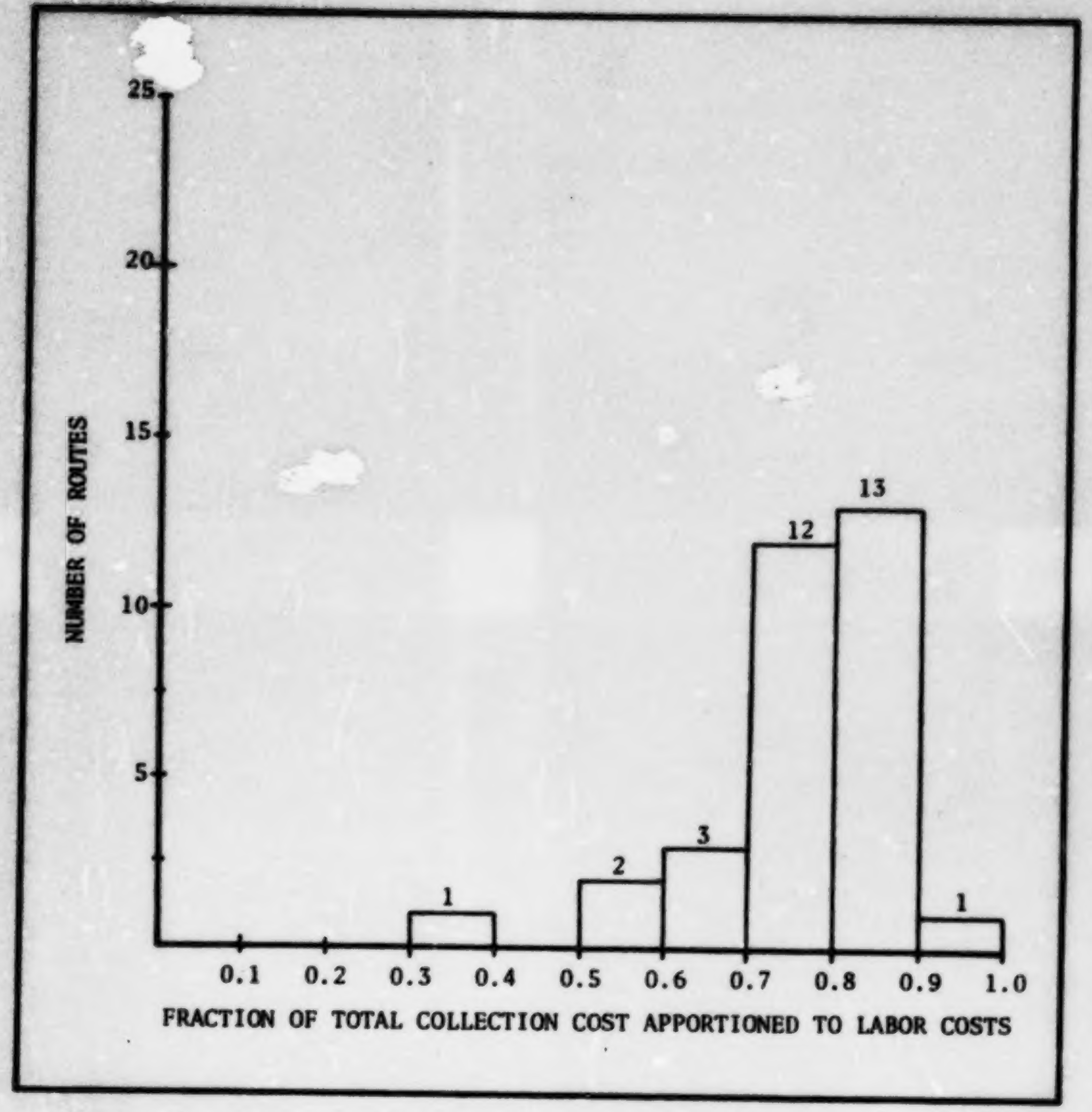


Figure 21: Histogram of Labor Cost Fraction of Total Refuse Collection Cost

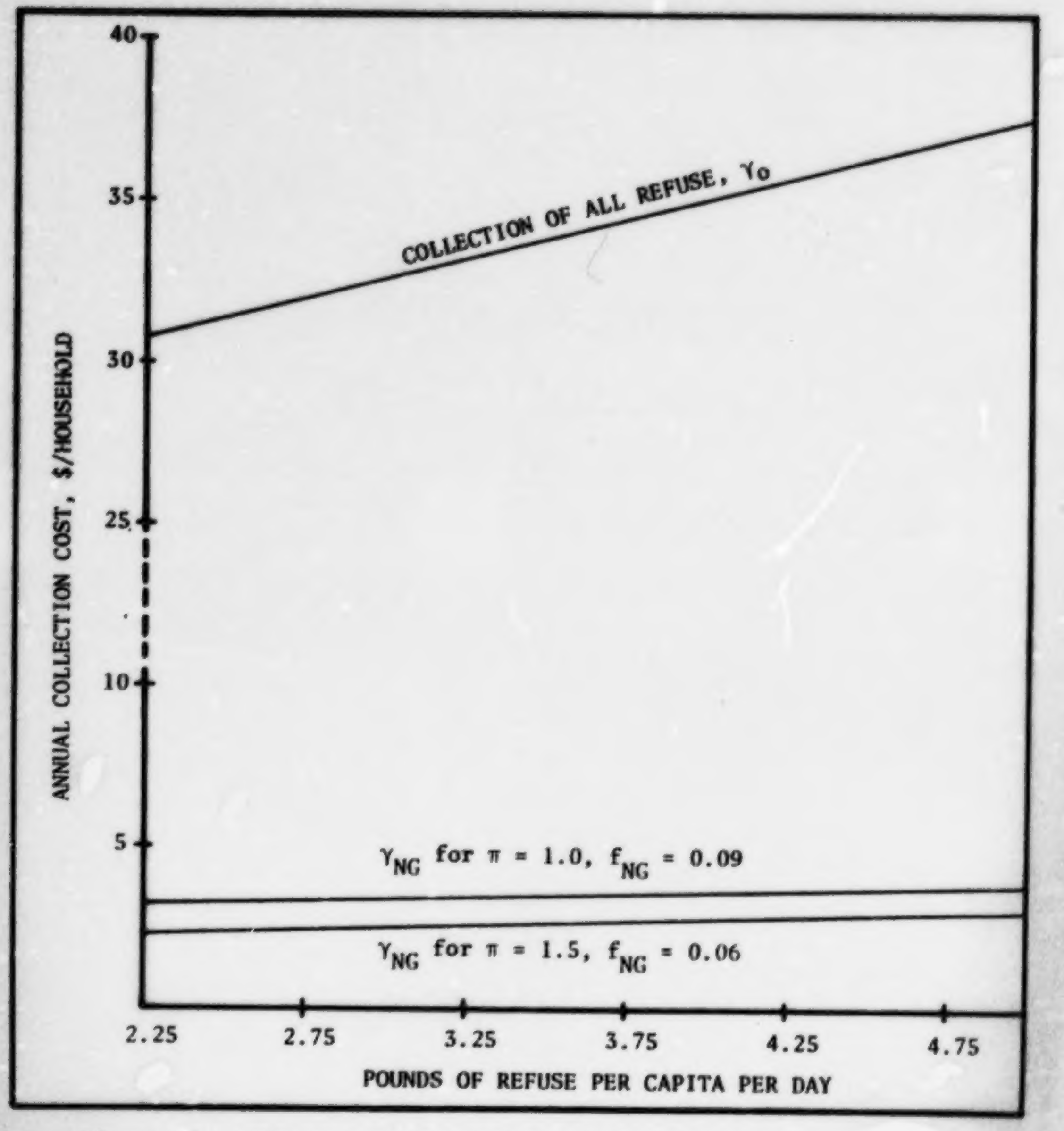


Figure 22: 1988 Cost of Collection of Nongrindables

In view of the uncertainties of market conditions for secondary recycled materials, we shall exclude any benefits accruing from resource recovery. This is a conservative assumption, because the potential for resource recovery from the wet systems concept is probably as great as that of conventional solid waste practice. For the purpose of comparison, we shall assume that conventional disposal will require incineration; and if resource recovery were to replace incineration in the case of conventional practice, it would also replace landfilling under the wet systems concept, with an equivalent net effect on total costs.

Costs for Landfilling of Nongrindables. The estimated 1973 costs for landfilling nongrindables are shown on Figure 24, the costs derived from the average cost function of Figure 23 which is based on a recent statewide solid waste management study for Massachusetts.[7] Because unit operating costs are strongly dependent on daily capacity, there are substantial economies of scale in total per household costs. The curves of 0.5, 1, 2 and 3 lb/household/day reflect 6, 12, 24 and 36 percent nongrindables at per capita generation rates of 2.25 lb/day. The 1988 landfill costs shown on Figure 25 reflect an increase of 2 percent per year of the labor fraction of the 1973 costs. Assuming that per capita refuse generation rates also increase by 2 percent per year, then the 1988 rate is 2.25 lb/cap/day x $(1.02)^{15}$ = 3.015 lb/cap/day. The curves shown for 1, 2 and 3 lb/household/day of nongrindables thus reflect 10, 20 and 30 percent of nongrindables.[8]

One may conclude that the absolute values of disposal costs are relatively insensitive to the percent of total refuse that cannot be ground; for example, an increase from 12 to 24 percent nongrindables would raise annual per household costs by only $0.50 in a city of 500,000 inhabitants. On the other hand, small communities would pay very much higher unit costs due to the very small amounts requiring landfill; for example, a city of 100,000 people would pay $2.40/year/household as against $0.80/year/household in a city of 500,000 people for the same 12 percent of nongrindables.

Cost Comparison. Generalizations for disposal costs under existing solid waste practices are difficult, if not impossible to undertake. Existing incineration costs are in the range of $5-$15/ton, or $7.50-$21.50 per household per year, to which must be added the cost of disposal of the noncombustible residuals. Figure 26 shows the operating costs of incinerators in Massachusetts, plotted against yearly capacity; only one of these incinerators meets existing air pollution criteria![9] With the new air pollution standards, most observers expect the cost of incineration to double, i.e. to $15.00-$43.00 per household per year. Many cities will go to other methods of disposal, but these are not expected to be much cheaper.

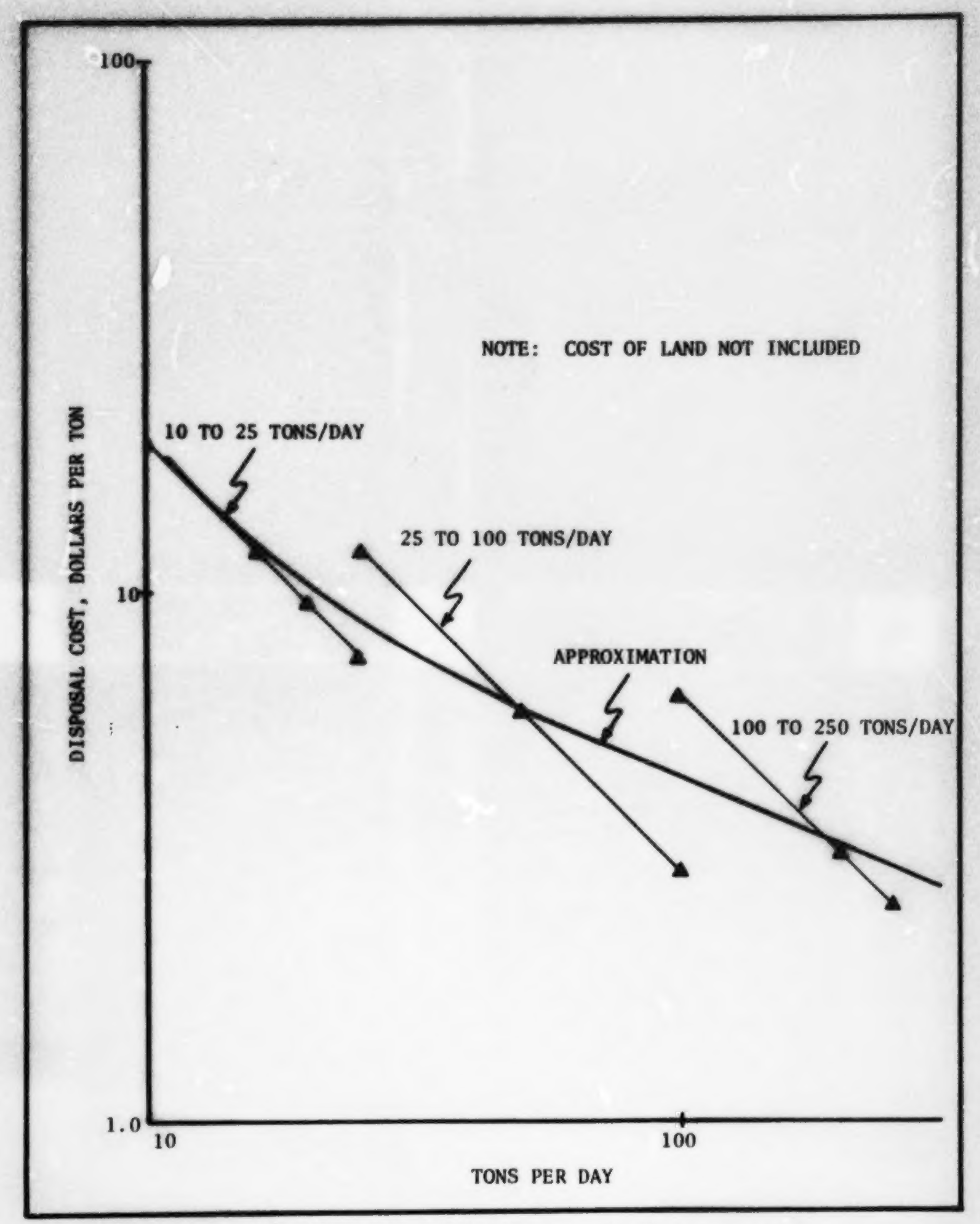


Figure 23: 1973 LANDFILL COSTS (Source: Raytheon, op. cit., Vol. III.)

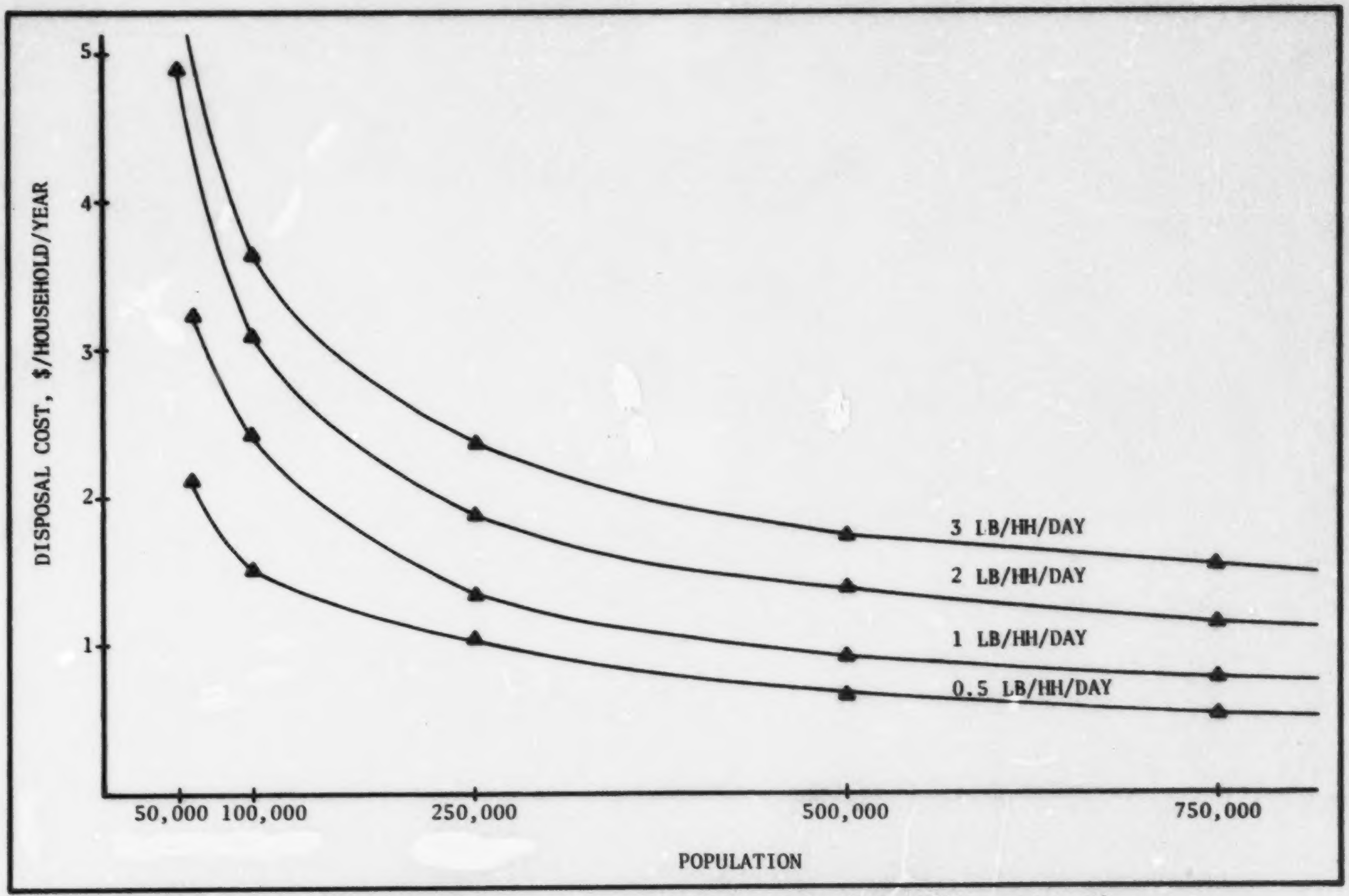


Figure 24: 1973 Disposal Costs for Nongrindables (For Explanation, see text).

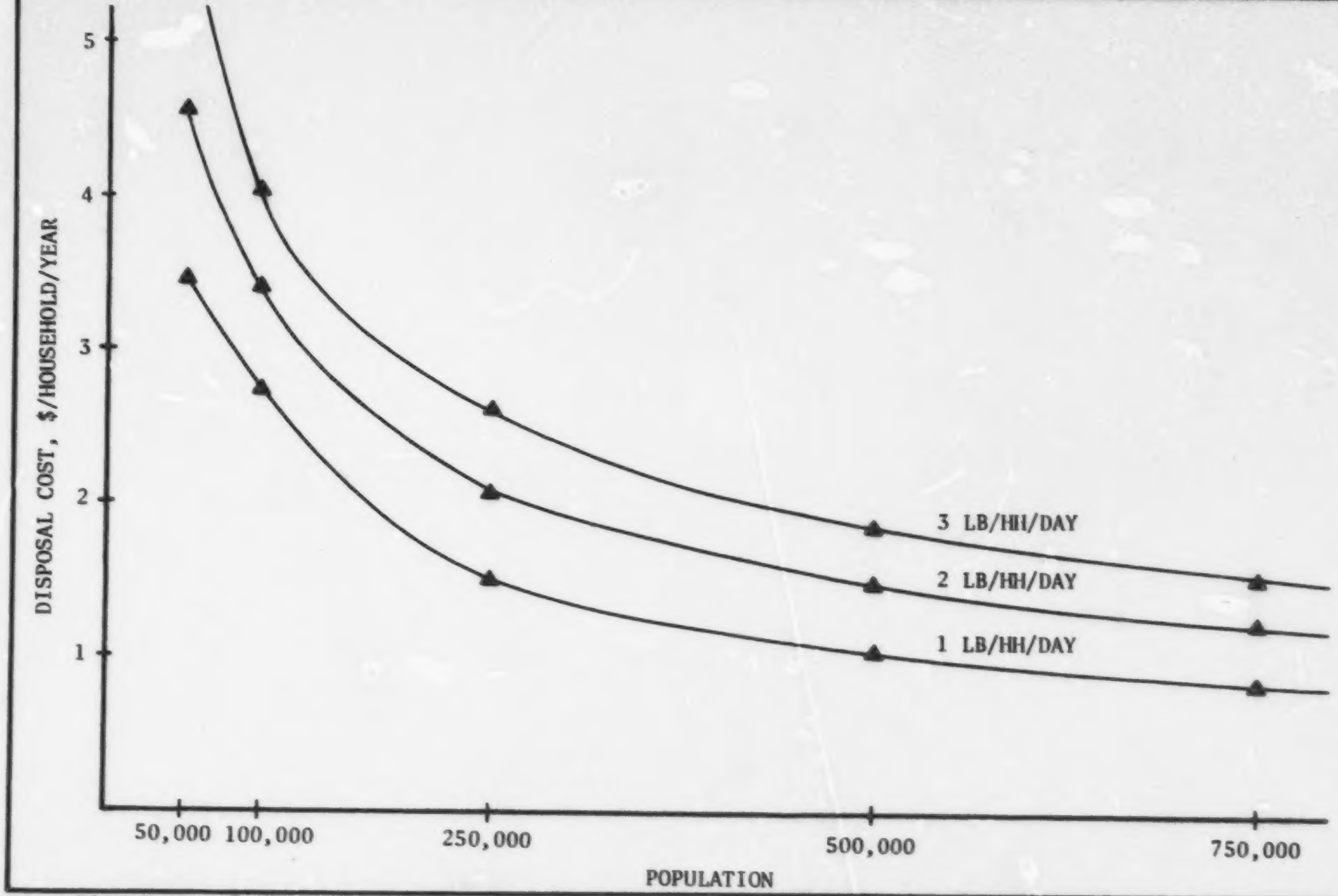


Figure 25: 1988 Disposal Costs for Nongrindables in 1973 Dollars (For explanation, see text.)

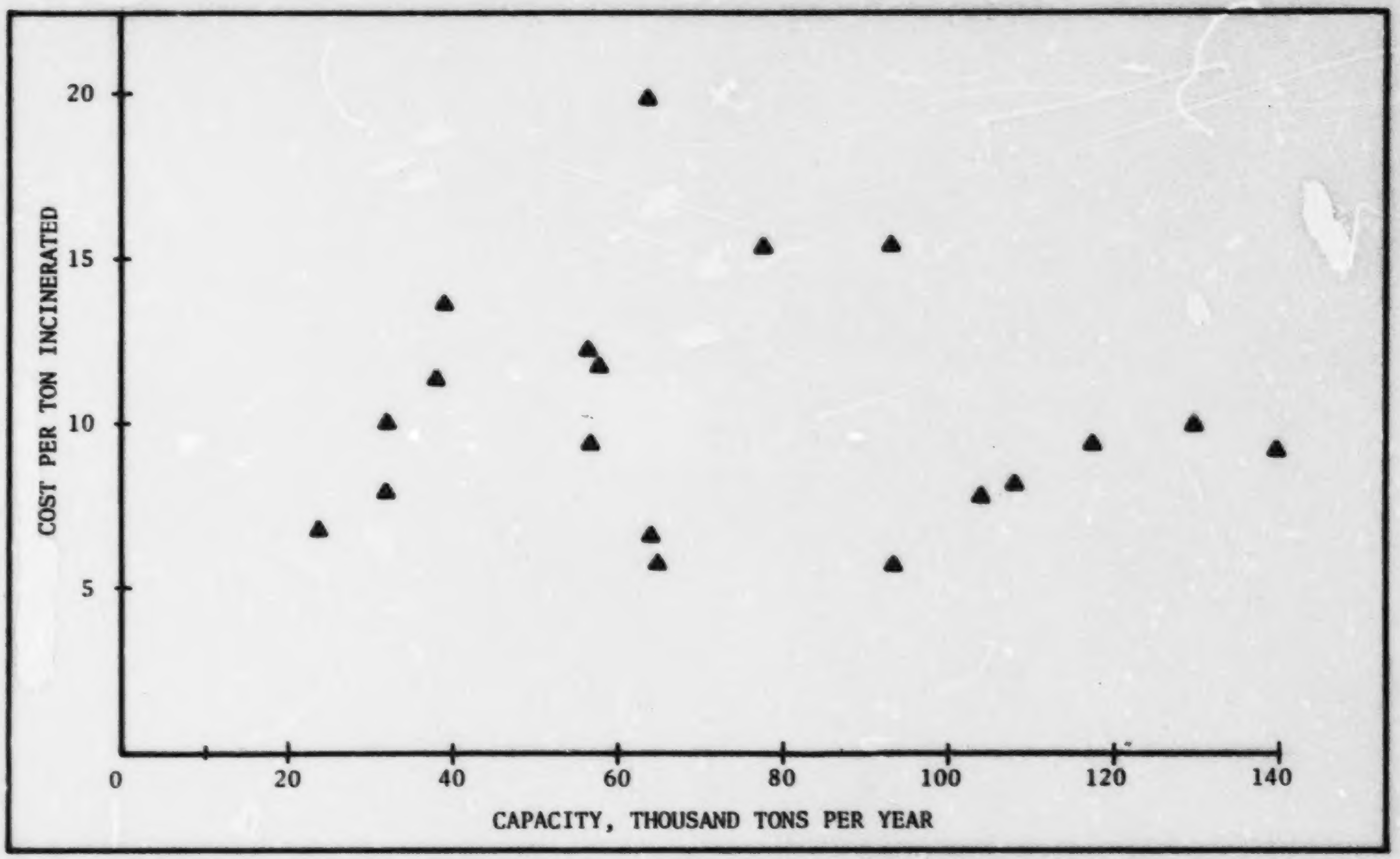


Figure 26: Operating Costs of 21 Incinerators in Massachusetts (Source: Raytheon op. cit., p. 2-157.)

Hydraulic Transport

Prior to a detailed case study, the costs of hydraulic transport of ground refuse are largely conjectural. However, upper and lower bounds for these costs can readily be established. Under the most favorable conditons, the only additional cost would be for some increased sewer repair and preventative maintenance. Under the most unfavorable conditions, a completely new sewer system would need to be built, as discussed in Chapter III. In other words, beyond a certain increased level of sewer maintenance it will be cheaper to build a new system built to new specifications of slope and minimum velocity adequate for ground refuse transport.

Existing Sewer Maintenance and Repair Costs. Average repair and preventative maintenance costs were developed in a recent paper by Santry.[10] The average number of repairs per mile of sewer is given as 2.2 per year, with an average cost of $162 per repair. Maintenance costs were given as $0.097 per foot of sewer per year. These can be converted to an annual per household cost using the equations for length of sewer per capita (ℓ) as a function of population density (x) and size of population (y) as given by Smith and Eilers.[11] These equations are

$$x = 0.3\, y^{0.304} \qquad [32]$$

$$\ell = 54\, x^{-0.65} \qquad [33]$$

where x is in persons per acre and ℓ is in feet of sewer per capita. Hence the annual per household cost for sewer maintenance and repair, Ω, is given by

$$\Omega = 3.5\, \ell\, (0.097 + \frac{2.2}{5280}\, 162) \qquad [34]$$

$$\Omega = 0.575 \qquad [35]$$

Sewer Maintenance and Repair Costs with Ground Refuse. In the absence of data under real conditions, a reasonable hypothesis is that maintenance and repair costs with ground refuse will be related to maintenance and repair costs without ground refuse, and that this relationship is some function of the increase in settleable solids. This relationship is postulated to be of the form

$$\Omega^* = \Omega \cdot (\frac{s^*}{s})^b \qquad [36]$$

Where Ω^* and Ω are the annual per household costs with and without ground refuse, s* and s the settleable solids concentration with and without ground refuse, respectively, and b is a coefficient.

The Upper Bound: Costs for a New Sewer System. Smith and Eilers give a cost function for the per capita construction cost of sewer systems as a function of population density, namely[12]

$$\sigma = 800x^{-0.775} \qquad [37]$$

Where σ is the per capita construction cost in dollars, and x the population density in persons per acre. Thus the annual per household cost μ^* is given by

$$\mu^* = 3.5 \cdot 800x^{-0.775} \cdot \mathrm{CRF}(i,n) \qquad [38]$$

Where CRF(i,n) is the capital recovery factor at interest rate i and period n. To this must be added the cost of maintenance of the new system, and thus the total annual per household cost is

$$\pi^* = \mu^* + \Omega \qquad [39]$$

This assumes that any reduction of maintenance due to lower maintenance requirements of a new system is offset by an equivalent increase in pumping cost.

Estimated Range of Costs. Figure 27 shows the values of annual per household sewer maintenance cost (Ω^*) as a function of population size (y) for selected ratios of s^*/s and coefficient values of b. The plot of $\Omega^* = f(y)$ for $b = s^*/s = 1$ reflects existing average maintenance costs. Superimposed on this is a plot of Equation (39) which shows the annual per household costs of new sewer construction.[13] It is clear that if actual values of s^*/s and b result in greater maintenance costs Ω^* than sewer construction costs π^*, then new system construction is preferable. Thus the expected range of hydraulic transport costs is shown by the hatched area of Figure 27. The upper and lower bounds as a function of population size can be summarized as shown on Table 11.

Table 11: 1973 Cost of Hydraulic Transport

Population Size	$/household/year Lower Bound	 Upper Bound
50,000	7.99	43.26
100,000	6.97	36.92
250,000	5.81	29.95
500,000	5.07	25.57
750,000	4.68	23.31
1,000,000	4.42	21.83

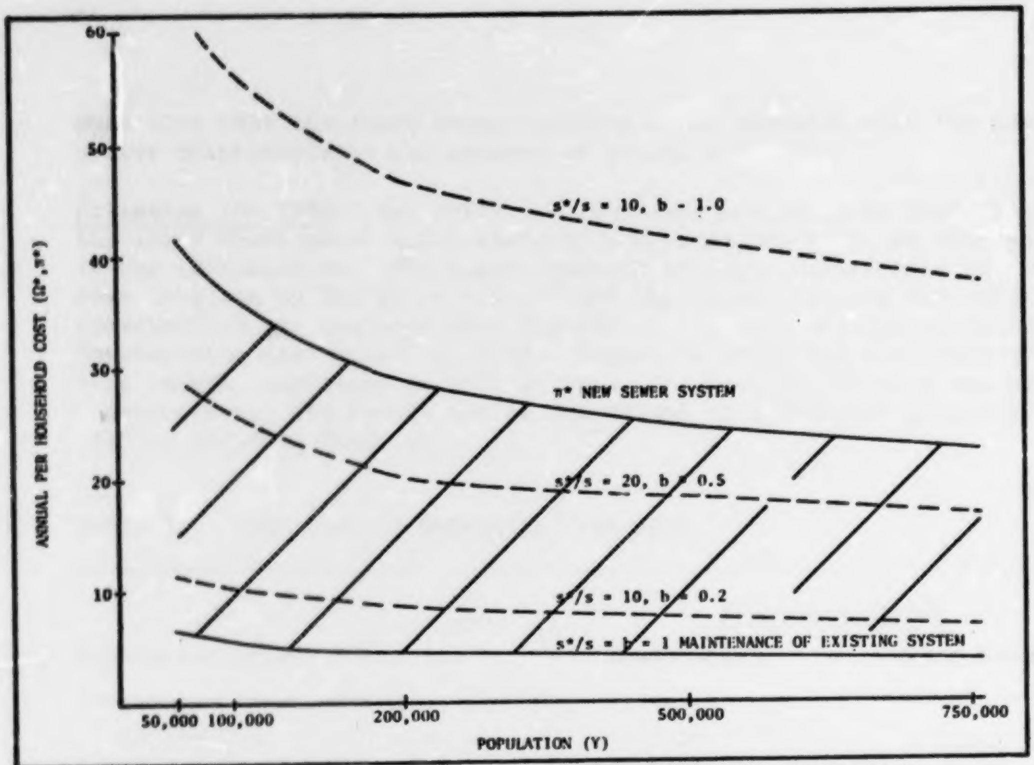


Figure 27: Annual Per Household Cost for Hydraulic Transport, 1973 Conditions

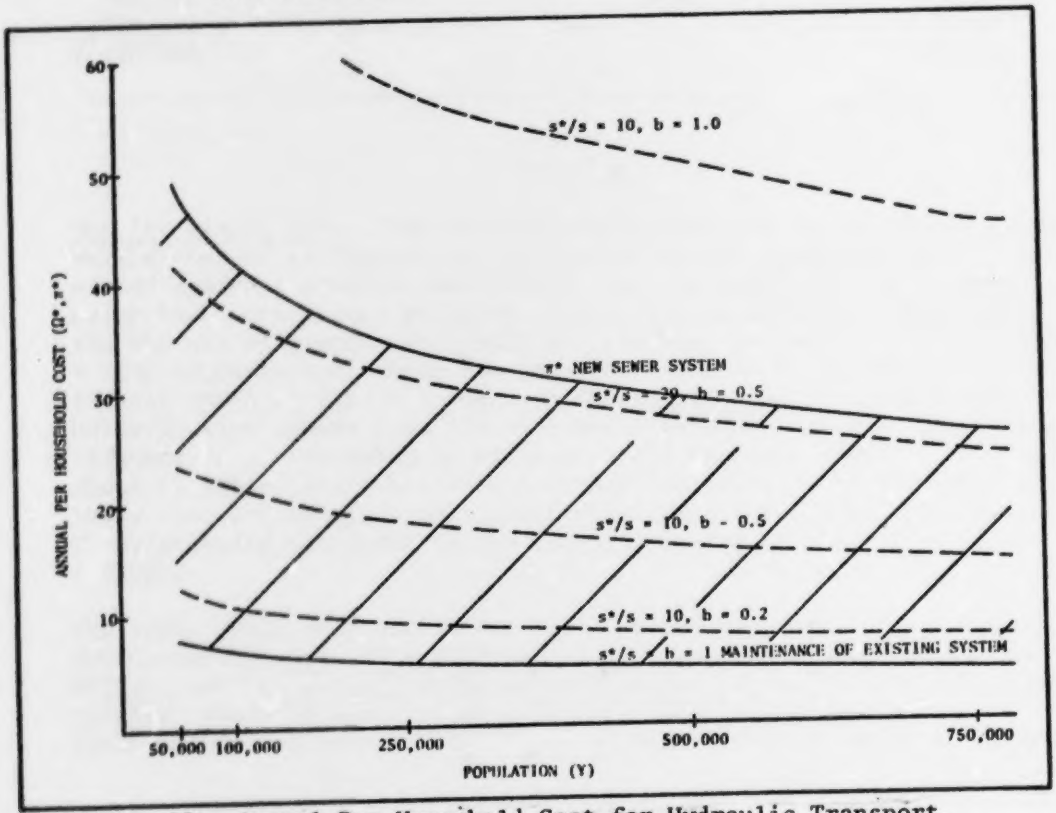


Figure 28: Annual Per Household Cost for Hydraulic Transport, 1988 Conditions, Expressed in 1973 Dollars

Note also that the lower bound represents the expected cost for sewer system maintenance in the absence of ground refuse.

Estimates for 1988. The costs for 1988 were developed by increasing the labor fraction of total costs by 2 percent per year, as rationalized in the introduction. The labor fraction of sewer maintenance and repair is given by Santry as 0.66,[14] and the labor fraction for sewer construction was computed from figures in the 1973 edition of Building Construction Cost Data[15] as 0.50. Figure 28 shows the resulting 1988 cost curves, expressed in 1973 dollars, for both maintenance and new construction. The bounds can be summarized as a function of population size as shown on Table 12.

Table 12: 1988 Cost of Hydraulic Transport

Population Size	$/household/year Lower Bound	 Upper Bound
50,000	9.82	51.19
100,000	8.56	43.70
250,000	7.14	35.46
500,000	6.23	30.28
750,000	5.75	27.61
1,000,000	5.43	25.86

Grinding

One Per Living Unit. Two possible configurations for household grinders were discussed in Chapter II; the Foster-Miller configuration, with reuse of nonfecal domestic wastewater, and the Meier-Nebiker scheme, using high consistency grinding, a pressurized building connection, and the use of laundry effluents for flushing purposes. Table 13 shows a cost comparison of these two schemes, based on Foster-Miller's estimates shown on Tables 1 and 2 of Chapter II. It is assumed that the Meier-Nebiker scheme uses the same basic grinder, but with an attached effluent pump, for which an additional $20 has been added.[16] The costs shown on Table 13 are based on a production level of 20,000 units per year. One may conclude that substantial cost savings may be effected by eliminating the plumbing separation required by the Foster-Miller concept.

The costs shown on Table 13 are for installation in existing buildings. Obviously, the cost of a plumbing separation in the case of the Foster-Miller concept, or a building connection in the case of the Meier-Nebiker concept, would be substantially less if these were effected at the time of construction. Foster-Miller estimated that additonal plumbing separation

Table 13: Cost Comparisons Between the Foster-Miller and Meier-Nebiker Concepts

		Foster-Miller (Grinding at 1% Solids with Wastewater Reuse)		Meier-Nebiker (Grinding at 7% Solids Discharge via pressurized building connection)	
Item	Assumed Life	Cost	Annual Cost at i = 6%	Cost	Annual Cost at i = 6%
Grinder	15	$180	$18.50	$200	$20.60
Installation	15	75	7.70	75	7.70
Distr. and Sales Costs	15	191	19.65	191	19.65
Storage Tank	30	116	8.40	0	0
Installation	30	75	5.40	0	0
Distr. and Sales Costs	30	143	10.40	0	0
Building Connection	30	0	0	450-500	32.60-36.30
Plumbing Modification	30	520-1,050	37.75-76.20	0	0
Total Initial Costs		1,300-1,830	108-146	916-966	80-84
Water			1.50		3.00
Power			2.50		2.50
Repairs			16.00		16.00
Total Annual Cost			128-166		101-105

costs for new construction would be in the range of $170-$270 if PVC pipe were used (see Table 1); this would reduce total initial cost of the Foster-Miller system from $1,300-$1,830 to $950-$1,050 and total annual cost, including operation and maintenance, from $128-$166 to $102-$110.

Similarly, the cost of a pressurized building connection would fall to about $315-$350,[17] resulting in a total initial cost for the Meier-Nebiker concept of $780-$815, and total annual cost would decrease to $90-95.

While these savings appear substantial, they must be viewed in the perspective of the slow rate of housing replacement in existing urban areas. Table 14 shows the age distribution of housing units in selected communities for the Springfield-Holyoke-Chicopee SMSA in Massachusetts; except for the rapidly growing areas of Longmeadow, Hampden and Wilbraham, new construction in existing urban areas is but a few percent per year of the existing housing, and consequently, the decreased installation costs would only apply to that small percent of the total existing housing inventory.

Table 14: Age Distribution of Housing in Selected Towns and Cities of the Springfield-Holyoke-Chicopee SMSA

	Age of Housing Units			
	Less than 10 years	10-20 years	20-30 years	More than 30 years
Chicopee	18	22	12	48
Holyoke	8	8	5	79
Springfield	8	17	11	64
Northampton	13	11	6	70
Longmeadow	31	24	8	37
E. Longmeadow	24	39	12	25
Hampden	43	24	8	11
Wilbraham	36	31	10	23
Monson	16	19	7	58

One Per Structure Grinders. As noted in Chapter II, the option of installing grinders on a one per structure basis is attractive from an economic viewpoint because of the economies of scale, and we have attempted to derive an upper cost bound for grinders installed on this basis. Curve A on Figure 29 shows the total amount of refuse generated per day per structure as a function of the number of households per structure. The capacity of the grinder would need to be much less than the daily total, because not all refuse need be ground at the same time.

However, there may be limitations in terms of the allowable hours of grinding because adequate flows may be present in the sewers only during a few hours every day. Therefore, we have made the conservative assumption that the grinder would need to be able to grind all the refuse generated in a structure in two grinding cycles, resulting in curve B of Figure 29 which shows the minimum capacity allowable as a function of households per grinder. Curve C on Figure 30 shows the initial cost of grinders expressed as the cost per pound of capacity. The exact economics of scale are unknown at present, but we have assumed, again conservatively, that the cost per pound of capacity will be 50 percent lower for a 10 fold increase in total capacity. The cost of capacity for the 8 lbs required by the one household per structure is taken from Table 15 ($200/8 = $25 per pound of capacity). Finally, curve D on Figure 30 shows the annual cost per household, obtained by multiplying curve B by curve C, amortizing over 15 years and 6 percent, and dividing by the number of households per structure.

Figure 31 shows the total annual per household costs as a function of the number of households per structure. Water and power requirements are assumed proportional to the amount of refuse ground, and therefore, the per household costs for water and power do not vary with the size of the grinder. Repairs are conservatively estimated as decreasing only from $16 per household to $8 per household; this implies that a grinder serving two households will have almost double the repair costs of a grinder serving one household; and a unit serving 6 households would have repair costs of $72/year. In view of the difficulties in ownership responsibility with one per structure grinders, mentioned in Chapter II, this high cost of repairs is not unreasonable.

Unit costs of installation and building connection are also conservatively estimated as decreasing by a factor of 4 and 3.5 respectively. Finally, by adding the annual cost of the initial grinder purchase, one obtains the total annual per household cost. For example, a grinder serving 5 householders is thus expected to cost no more than $76/year per household, that is, at least a 25 percent reduction over grinders installed on a one per living unit basis.

The impact on average costs of the one per structure approach can be seen from Table 15, which shows a computation for a hypothetical city of 25,000 households with a typical mix of housing types. Annual average costs are seen to fall from $100 per household for one per living unit to a citywide average of $85.

Neighborhood Grinders. On the basis of the experience with the Black-Clawson process,[18] and the experience of the pulp and paper industry as a whole, it appears that hydropulpers as designed and used in the paper industry would be suitable as neighborhood grinders. Ferrous metals are not ground and ejected automatically, as in the Foster-Miller design. But all the other components of refuse are ground, including glass and aluminum, resulting in a discharge to the sewer that is similar to that of the Foster-Miller design. Our cost estimates for

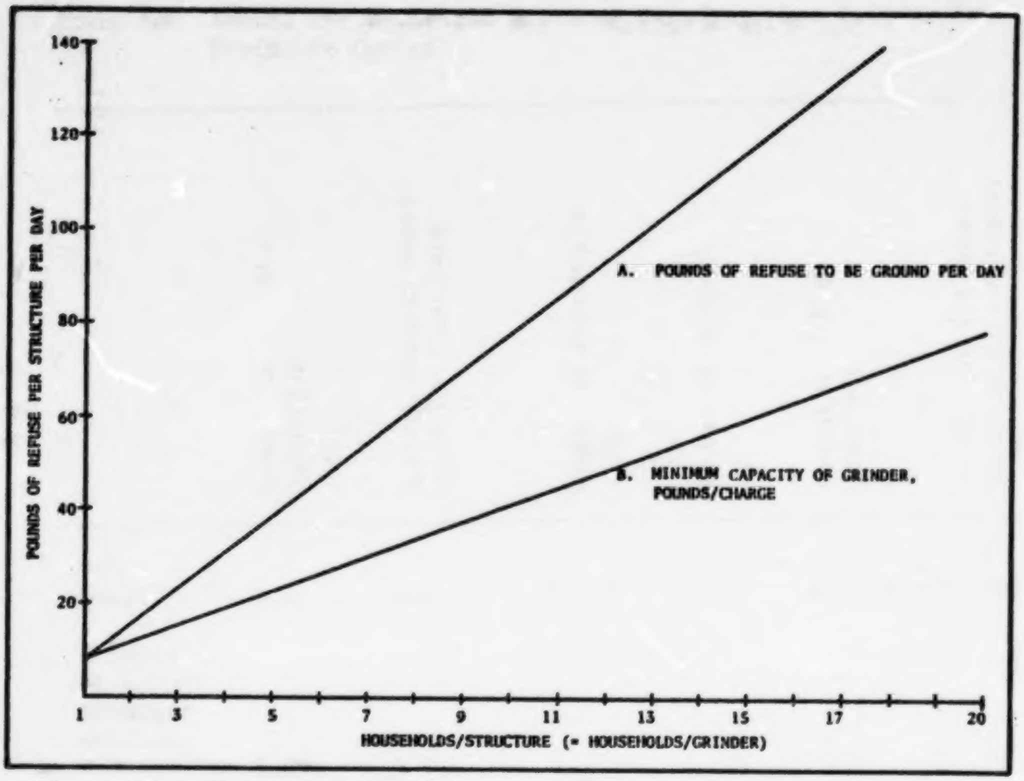


Figure 29: Capacity of Grinder as a Function of Households per Structure

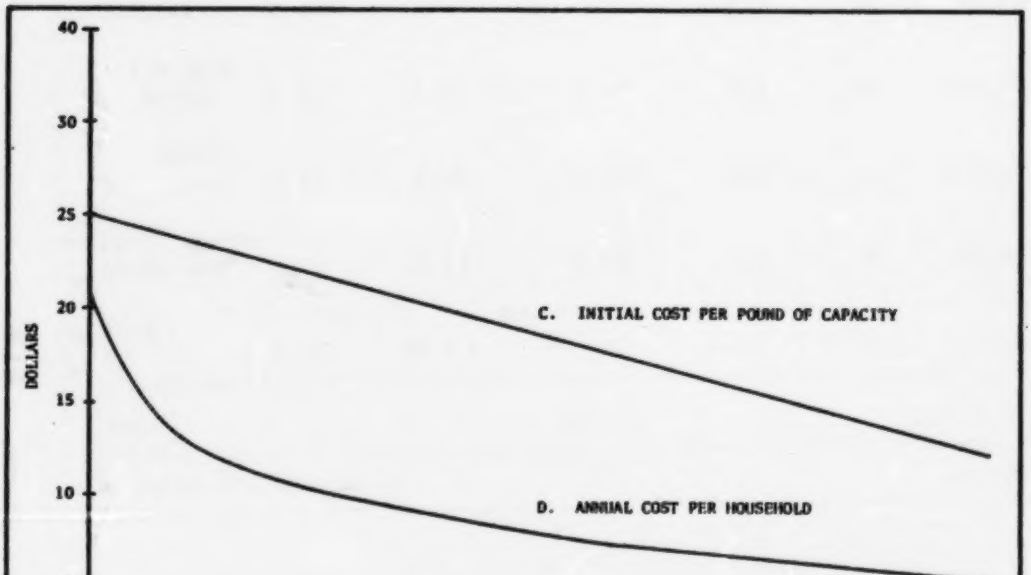


Figure 30: Grinder Costs as a Function of Households per Structure

Table 15: Annual Per Household Costs of Grinding, One Grinder Per Strubture Option

	Proportion of Total Households	Average Assumed Households Per Structure	Number of Households	Number of Grinders	Annual Cost Per Household	Total Cost all Households in this Category
Single Family	0.5	1.0	12,500	12,500	$100	$1,250,000
2 Units/ Structure, Arranged Horizontally	0.085	2.0	2,125	2,125	100	212,500
2 Units/ Structure, Arranged Vertically	0.085	2.0	2,125	1,065	92	195,500
3 & 4 Units/ Structure	0.10	3.50	2,500	710	82	205,000
5-9 Units/ Structure	0.10	6.50	2,500	380	70	175,000
10-50 Units/ Structure	0.10	20.00	2,500	120	30	75,000
More than 50	0.03	60.00	750	10	30	22,500
Total			25,000			$2,135,500
Average Per Household						$85

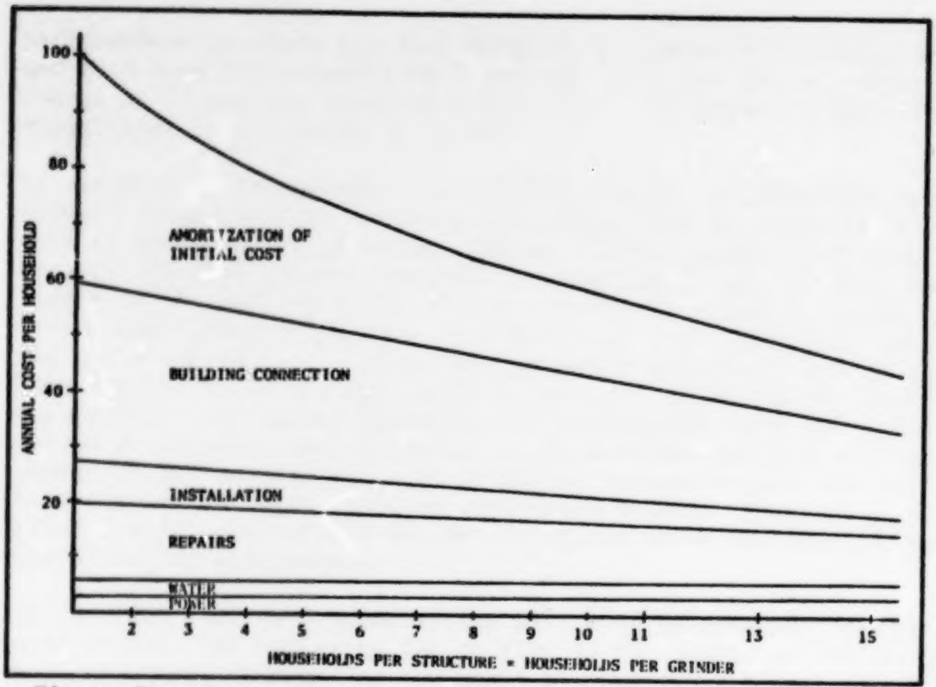


Figure 31: Total Annual Cost for One Per Structure Grinders

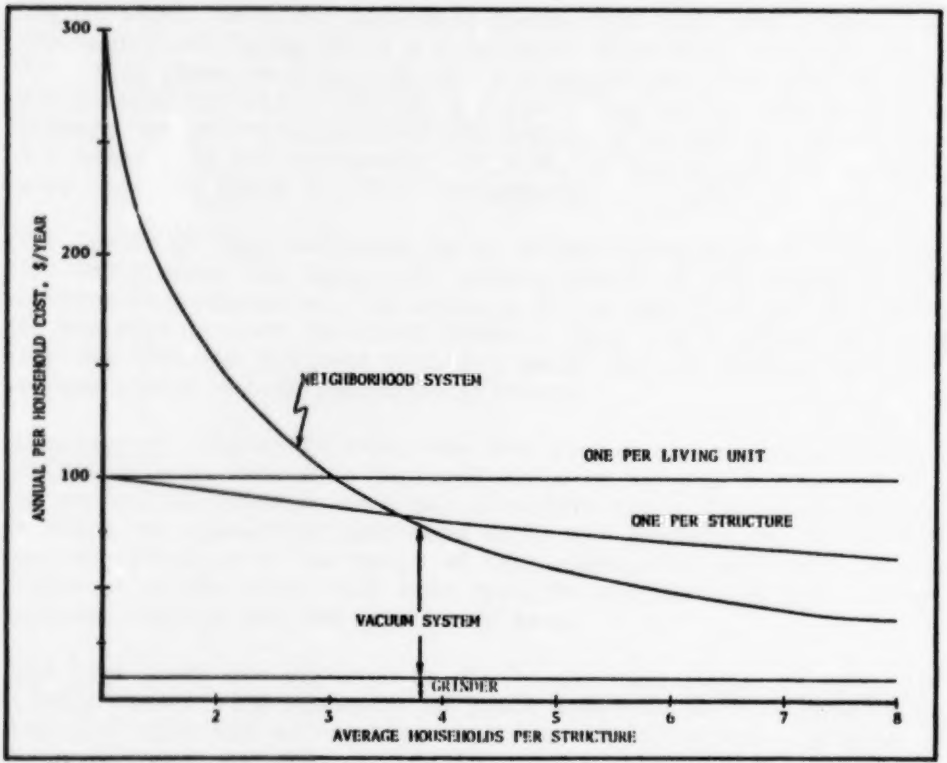


Figure 32: Cost Comparisons of Neighborhood, One Per Structure and Living Unit Grinders

neighborhood grinders are thus based on a commercially available Noble and Wood Mark III pulper with a capacity of 2,600 lbs of refuse per charge at 12 percent grinding consistency. As shown on Table 16, the annual cost is estimated at $7,400.

In addition to the grinder installation itself, neighborhood grinders require vacuum systems to bring the refuse from the individual living unit to the point of grinding. Unfortunately, generalized cost estimates for such vacuum systems are unavailable, and the only useful source is the work by Zandi.[19] For a total of 22,000 building connections, the installation cost, including the steel pipeline, excavation, air seals and house fittings, was estimated in 1966 at $47 million. This results in an average installation cost of $2,140 per building connection. The annual operation and maintenance cost for a design period of 50 years was estimated at $15 million, and the average annual operation and maintenance cost of pipes, vacuum blowers and seals is then $14 per building again at 1966 price levels. Updated to 1973 price levels, one obtains $3,780 for installation and $25 per year for operation and maintenance.

It is clear that the vacuum system will only be economic in high density areas. One criterion for density is the number of living units per structure, thus having the merit of permitting direct comparisons with the one per structure and one per living unit grinder options. Amortizing over 30 years at 6 percent, the total annual cost per building is $300. On a per household basis, this cost would diminish as the number of living units per building increased, as shown on Figure 32. Also shown on Figure 32 are the annual per household costs for one grinder per structure and one per living unit. The breakeven point between one per structure and one per neighborhood is seen to be at 3.5 households per structure. Thus any neighborhood with a higher density than 3.5 would justify a neighborhood grinder.

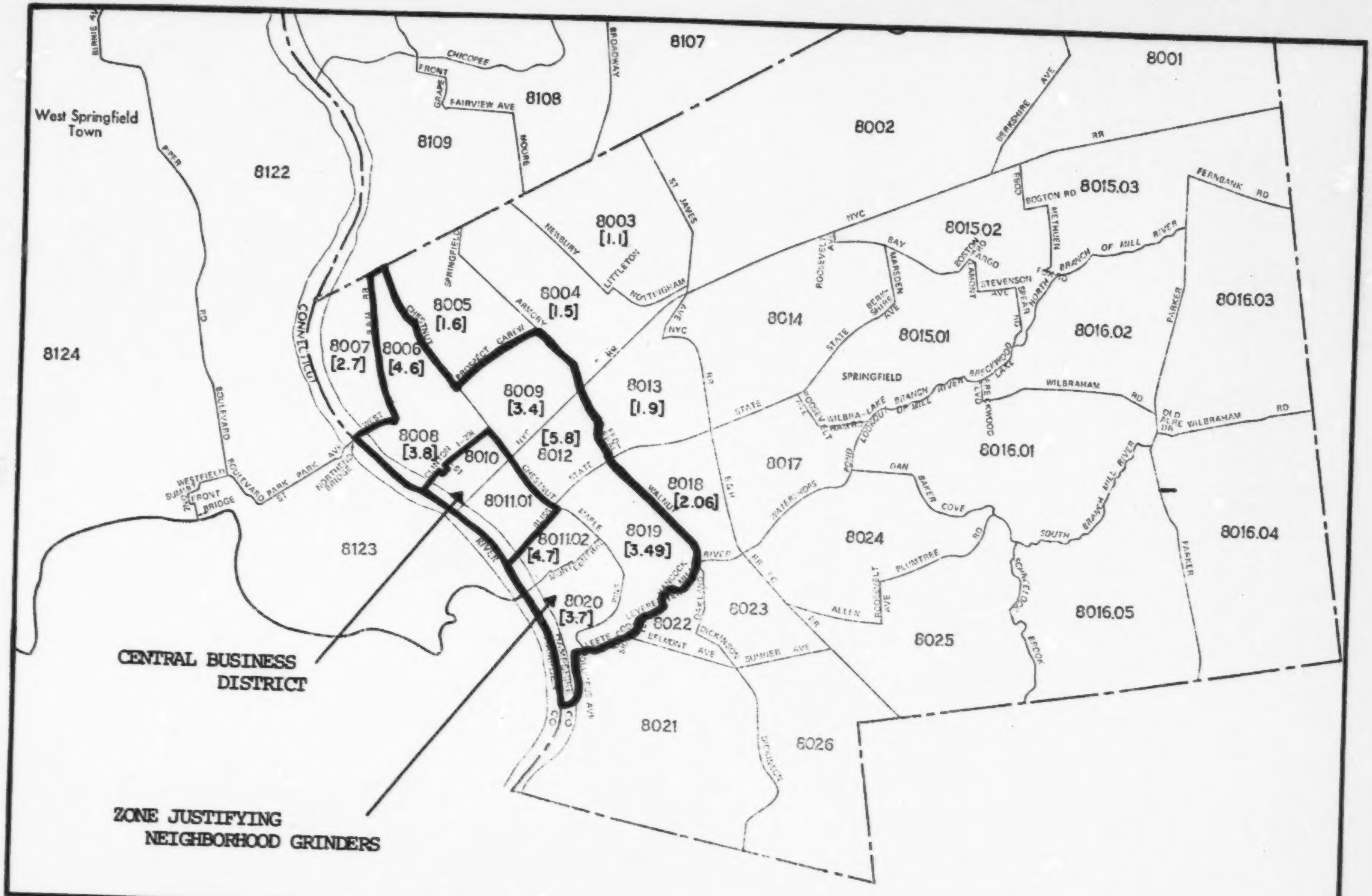
The impact of this criterion on an actual urban area is shown on Figure 33, which shows the inner city census tracts of the Springfield SMSA in western Massachusetts: the average living units per structure are shown in brackets beneath the tract number. Only the 7 census tracts surrounding the downtown business district would thus be candidates for the vacuum system and neighborhood grinders.

Conclusion. Figure 32 shows how the average per household costs for grinding in an area-wide implementation of the wet system can be lowered by installing grinders on a per structure and a per neighborhood basis. A range for annual per household costs for grinding of $80 to $105 would appear realistic on the basis of the information available at this time. Phase II of the study will make specific estimates of the alternative grinder options for the case study area.

The 1988 costs are expected to lie in the same range, if not substantially lower. The economies of scale inherent in mass production, and the fact that the wet systems approach, if universally adopted, would

Table 16: Sample Cost Estimates for the Noble & Wood Pulper as a Neighborhood Refuse Grinder

Number of Households Served	1,150
Cost Data	
Capital Cost, $	44,000.00
Installation Cost	5,500.00
Total Initial Cost	49,500.00
Life of Unit, Years	30.00
Operating Characteristics	
Grinding Concentration, Percent	12.00
Grinding Time, Mins.	20.00
Total lbs Ground/Day	5,752.74
Loads/Day	3.00
Time Operating Hours	1.00
Operating Efficiency	0.4
Pounds Per Charge	2,600.00
Grinding Water Requirement (gals)	5,748.14
Sewage Available for Grinding (gals)	181,124.94
Freshwater Requirement, Gals/Day	287.41
Annual Costs Per Unit	
Maintenance and Repair Cost, $/Year	2,500.00
Operating Cost % Water, $/Year	209.81
Operating Costs % Power, $/Year	707.95
Total OMR Costs, $/Year	3,417.76
Amortized Initial Cost, $/Year	3,989.03
Total Cost, $/Year	7,406.79


West Springfield Town
8124
8122
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[1.1]
8004
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[1.6]
8006
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[2.7]
8008
[3.8]
8009
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8016.02
8016.03
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8018
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8019
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8020
[3.7]
8021
8022
8023
8024
8025
8026
SPRINGFIELD
CONNECTICUT
RIVER
CHICOPEE
FRONT
GRAPE
FAIRVIEW AVE
MOORE
BROADWAY
ST JAMES
NEWBURY
LITTLETON
NOTTINGHAM
SPRINGFIELD
CHESTNUT
PROSPECT
CAREW
ARMORY
NYC
RR
STATE
MAPLE
BERKSHIRE AVE
BOSTON RD
COBB
METHUEN
ROOSEVELT AVE
BAY
MARSDEN
BERKSHIRE AVE
STEVENSON AVE
LAMONT
SPEAR
FERNBANK RD
PARKER
WILBRAHAM RD
OLD ACRE DR
WILBRAHAM RD
BRECKWOOD BLVD
WILBRA-LAKE
LOOKOUT
BRANCH OF MILL RIVER
LAKE
POND
WATERSHOPS
B&H
DAN
BAKER
COVE
RD
SOUTH BRANCH MILL RIVER
PLUMTREE
ALLEN
SCANTIC BROOK
BELMONT AVE
SUMNER AVE
DICKINSON
OAKLAND
LEETE
PINE
OLIVER ST AVE
HAMPDEN CO
WALNUT
PIPER
RD
BOULEVARD
PARK AVE
PARK ST
NORTH END BRIDGE
WESTFIELD
SUMNER
FRONT
BRIDGE
BIRNIE AV
CENTRAL BUSINESS DISTRICT
ZONE JUSTIFYING NEIGHBORHOOD GRINDERS

Figure 33: Census Tracts in Springfield, Mass. (Source: U. S. Census of Housing, PHC(1) - 205.)

require a production level of about 0.95 million grinder units per year,[20] would almost certainly bring cost reductions. If the market for 0.95 million units annually were split evenly between 10 major appliance manufacturers at 100,000 units per year, unit costs would doubtless be lower than those estimated by Foster-Miller for 20,000 per year.

Treatment

The cost calculations for treatment are based on the results generated by a modified version of the Executive Digital Computer Program for preliminary design of wastewater treatment systems developed by Smith and Eilers.[21] A large number of additional treatment processes were added to the latest version of the program in addition to a major expansion and restructuring so as to accommodate 100 processes, 50 quality parameters and 200 streams whilst keeping to the same core storage restriction[22] (as opposed to 25 processes, 20 quality parameters and 25 streams in the original Smith and Eilers version). This modified program is documented in a separate report.[23]

We have not included a process-by-process cost breakdown of the estimates presented in this section so that the primary intent of the analysis, which is to establish the order of magnitude of costs and to compare this to existing treatment costs, is not obscured. The detailed systems analysis of treatment alternatives and the development of a preliminary design are tasks that will be undertaken in Phase II. Moreover, although the newly developed treatment process routines in the computer model are all fully operative, the design relationships upon which the costs are based have not yet been fully optimized, and thus a presentation of cost and design details for each unit operation would be somewhat premature.

Process Configuration 1. This configuration is shown on Figure 34, and represents one of the treatment plant alternatives suggested by Metcalf & Eddy in their preliminary cost estimates.[24] Metcalf & Eddy estimated only the capital costs of this treatment configuration of a 1 mgd facility at $1.6 million for sewage alone, and $7.4 million with ground refuse.[25]

As evidenced by Table 17, the computer model yields comparable results for the case of sewage alone, but gives a very much lower cost for the addition of ground refuse. It is interesting to note, however, that early runs with the computer model yielded comparable results to the Metcalf & Eddy estimates, but close examination of these runs showed that costs could be significantly reduced by control of a few key operating parameters. For example, by running the vacuum filter at 2 shifts per day rather than 1 shift, significant economies could be attained. This would be unconventional at an existing 1 mgd facility handling only sewage, but the great increase in total solids handled when ground refuse is added makes for a much larger overall operation

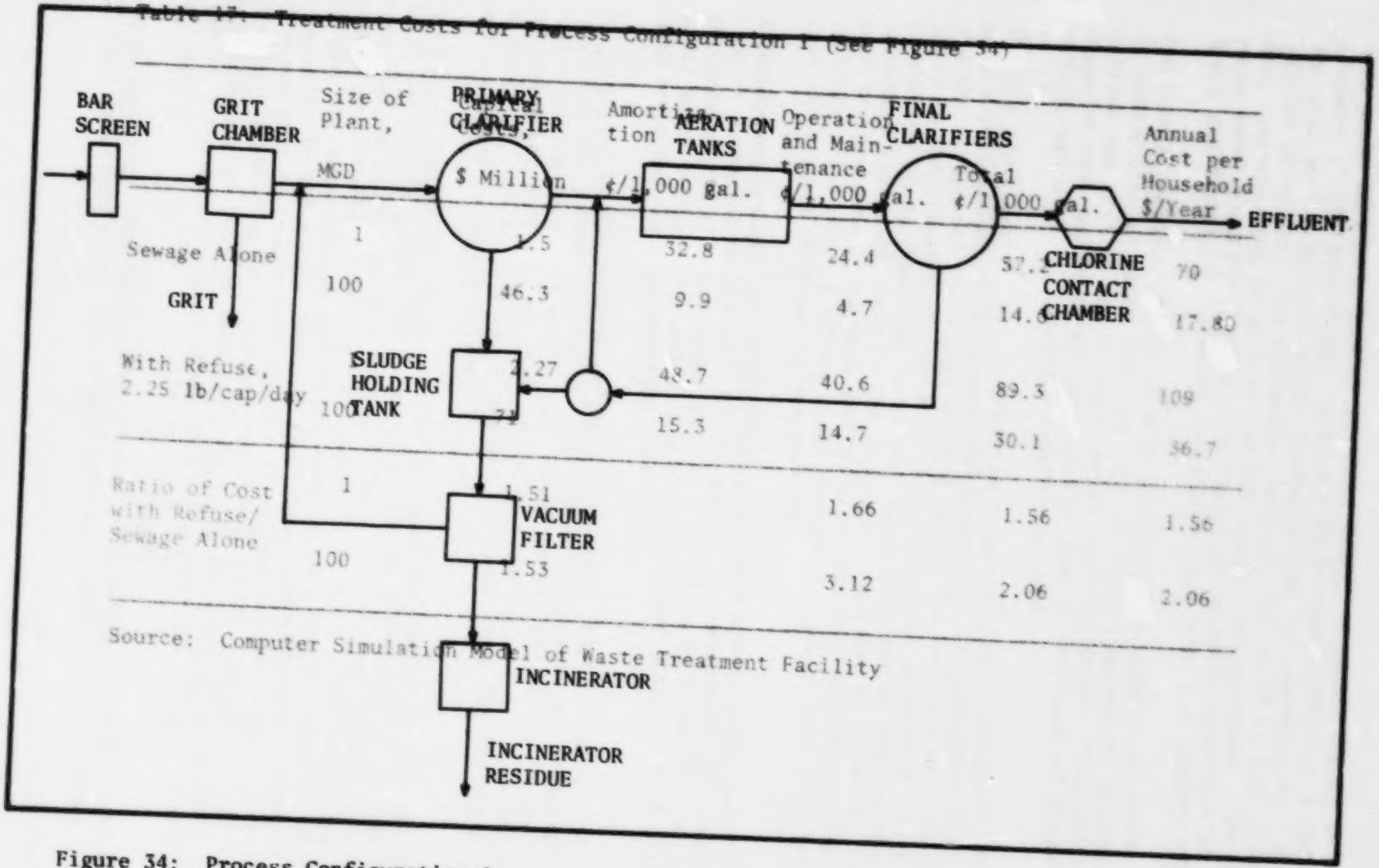
BAR SCREEN
GRIT CHAMBER
GRIT
PRIMARY CLARIFIER
SLUDGE HOLDING TANK
VACUUM FILTER
INCINERATOR
INCINERATOR RESIDUE
AERATION TANKS
FINAL CLARIFIERS
CHLORINE CONTACT CHAMBER
EFFLUENT

Figure 34: Process Configuration 1

Table 17: Treatment Costs for Process Configuration 1 (See Figure 34)

	Size of Plant, MGD	Capital Costs, $ Million	Amortization ¢/1,000 gal.	Operation and Maintenance ¢/1,000 gal.	Total ¢/1,000 gal.	Annual Cost per Household $/Year
Sewage Alone	1	1.5	32.8	24.4	57.2	70
	100	46.3	9.9	4.7	14.6	17.80
With Refuse, 2.25 lb/cap/day	1	2.27	48.7	40.6	89.3	109
	100	71	15.3	14.7	30.1	36.7
Ratio of Cost with Refuse/ Sewage Alone	1	1.51		1.66	1.56	1.56
	100	1.53		3.12	2.06	2.06

Source: Computer Simulation Model of Waste Treatment Facility

that would certainly justify a second shift. A second source of discrepancy is the much higher total solids assumed by Metcalf & Eddy, who used an 0.5 percent solids concentration corresponding to 5 lb/cap/day of refuse. Our estimates, however, are based on 2.25 lb/cap/day, corresponding to an 0.25 percent solids concentration. The computer model incorporates the cost functions recently developed by Black and Veatch, and updated to reflect cost levels of January 1973.[26]

The results shown on Table 17 show substantial economies of scale. It should also be noted that the cost of final disposal of incinerator residue and grit is not included in the cost estimates. This ultimate disposal cost may be significant in the case of treatment of ground refuse, and will be considered separately below.

Process Configuration 2. As shown on Figure 35, this configuration adds a grit washer, a thickener, and a digester to Configuration 1, and has eliminated the sludge holding tank. The addition of a thickener prior to the digester was shown by some early runs to substantially decrease the sludge handling costs over those obtained by routing the secondary sludge directly to the digester. As shown on Table 18, the cost of treatment using this configuration has decreased significantly, although still showing strong scale economies. Again, note that the cost of ultimate disposal is not included.

A comparison between the costs yielded by the computer model and estimates developed by Eilers[27] may be useful to demonstrate the reasonableness of the computer model results. As shown on Table 19, the computer model construction costs show good agreement with those of Eilers updated to the same construction cost index.

Alternatives to Conventional Primary Treatment. The possibility of replacing the primary clarifier by a series of screens was examined, with a coarse screen (4 mesh), and a fine screen (60 mesh), in series, replacing the primary clarifier of process configuration 2. As shown on Table 20, the difference in overall treatment cost for 250 mgd plant was not found to be significant.[28]

Per Capita Generation Rates. Table 21 shows the impact of increasing daily per capita generation rates from 2.25 to 3.375 and 4.5 lb/cap/day. Note that doubling the load from 2.25 to 4.5 lb/cap/day increases total annual per household costs by only about 50 percent. The reason for this is that increased refuse generation results in a larger treatment plant, especially in the sludge handling facilities, and therefore economies of scale tend to reduce unit costs. If one assumes an annual increase of refuse generation of 2 percent over the existing rate of 2.25 lb/cap/day, the average rate by 1988 would be 3.015 lb/cap/day, which would result in a treatment cost of about $0.23/1,000 gal. or $28 per household per year.

Sludge Handling. The annual cost of sludge handling, and the fraction of total treatment costs that sludge handling represents, are shown

Table 18: Treatment Costs for Process Configuration 2

	Size of Plant, MGD	Capital Costs, $ Million	Amortization ¢/1,000 gal.	Operation and Maintenance ¢/1,000 gal.	Total Cost ¢/1,000 gal.	Annual Cost per Household $/Year
Sewage Alone	10	4.70	10.0	7.2	17.2	21.0
	25	9.37	8.0	5.3	13.3	16.2
	50	16.8	7.2	4.3	11.5	14.0
	100	31.2	6.7	3.6	10.3	12.6
With 2.25 lb/cap/day of Refuse	10	[illegible]	[illegible]	12.1	29.2	35.6
	25	[illegible]	[illegible]	8.9	25.2	28.3
	50	30.7	[illegible]	7.5	20.6	25.2
	100	57 9	12.4	6.6	19.0	23.2

Source: Computer Simulation Model of Waste Treatment Facility

Table [illegible]: Comparison of Computer Model Cost Estimates

	Construction, Amortized Annual Cost, ¢/1,000 gal.		
	Computer Model (CCI = 176.1)	Eilers, Published Values (CCI = [illegible])	Eilers, Updated Values (CCI = 176.1)
10 MGD	[illegible]	[illegible]	10.2
100 MGD	[illegible]	[illegible]	6.5

CCI = Sewage Treatment Plant Construction Cost Index

Source: Table 18 and Eilers, op.cit., Tables 3 and 4.

Table 20: Replacement of the Primary Clarifiers of Treatment Configuration 2 by Screens (50 mgd)

	Capital Costs, $ Million	Amortization ¢/ 1,000 Gal.	Operation & Maintenance [illegible]	Total ¢/1,000 Gal.	Annual Cost per Household $
Sewage Alone	16.8	7.2	4.3	11.5	14.00
2.25 lb/cap/day Refuse, Primary Clarifiers	30.7	13.1	7.5	20.6	25.20
[illegible] lb/cap/day Refuse, Screens	31.0	13.2	8.0	21.2	25.90

Source: Computer Simulation Model of Waste Treatment Facility

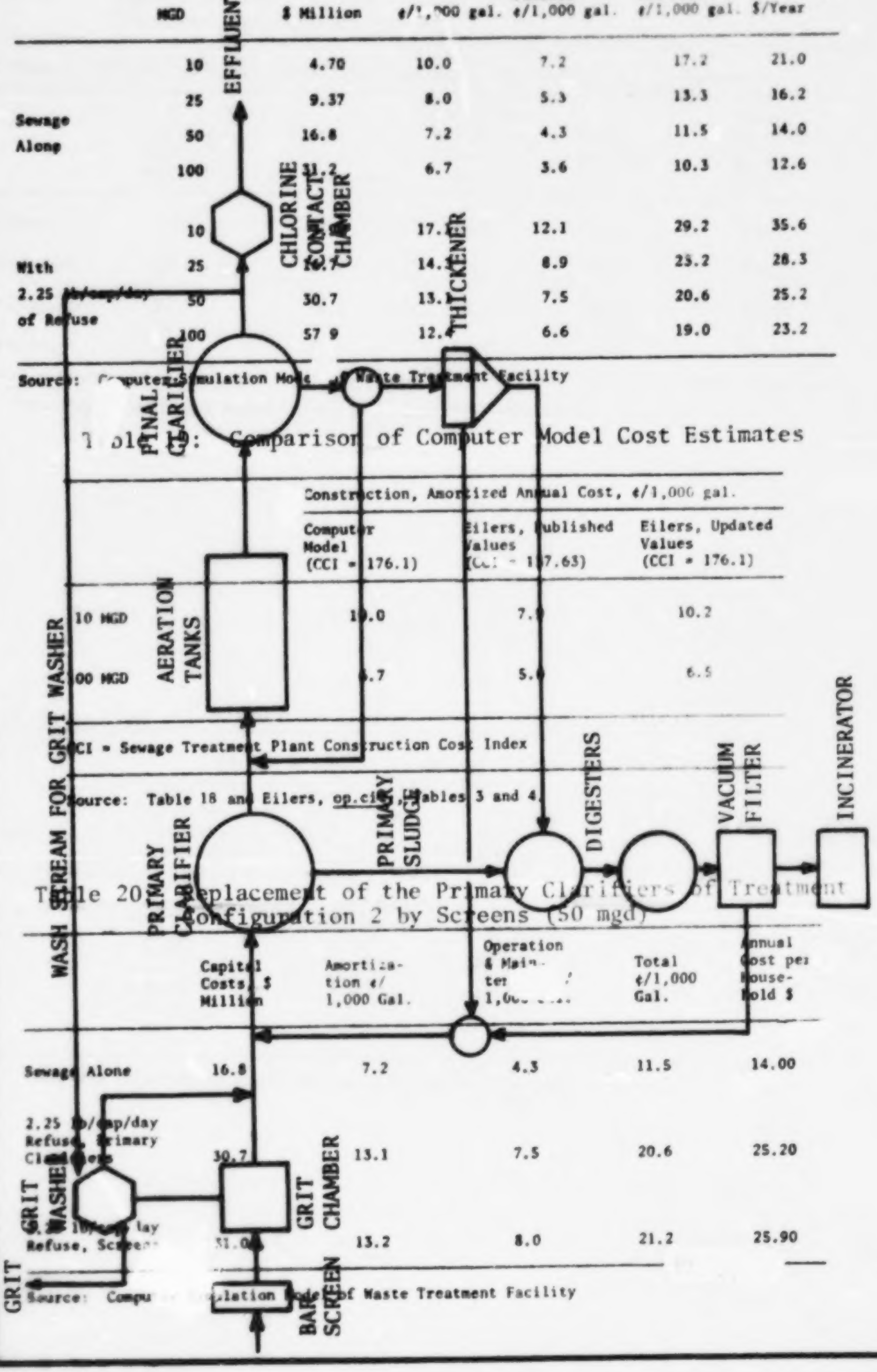
EFFLUENT
CHLORINE CONTACT CHAMBER
THICKENER
FINAL CLARIFIER
AERATION TANKS
WASH STREAM FOR GRIT WASHER
PRIMARY CLARIFIER
PRIMARY SLUDGE
DIGESTERS
VACUUM FILTER
INCINERATOR
GRIT WASHER
GRIT CHAMBER
BAR SCREEN
GRIT

Figure 35: Process Configuration 2

Table 18: Treatment Costs for Process Configuration 2

	Size of Plant, MGD	Capital Costs, $ Million	Amortization ¢/1,000 gal.	Operation and Maintenance ¢/1,000 gal.	Total Cost ¢/1,000 gal.	Annual Cost per Household $/Year
Sewage Alone	10	4.70	10.0	7.2	17.2	21.0
	25	9.37	8.0	5.3	13.3	16.2
	50	16.8	7.2	4.3	11.5	14.0
	100	31.2	6.7	3.6	10.3	12.6
With 2.25 lb/cap/day of Refuse	10	7.99	17.1	12.1	29.2	35.6
	25	16.7	14.3	8.9	23.2	28.3
	50	30.7	13.1	7.5	20.6	25.2
	100	57.9	12.4	6.6	19.0	23.2

Source: Computer Simulation Model of Waste Treatment Facility

Table 19: Comparison of Computer Model Cost Estimates

	Construction, Amortized Annual Cost, ¢/1,000 gal.		
	Computer Model (CCI = 176.1)	Eilers, Published Values (CCI = 137.63)	Eilers, Updated Values (CCI = 176.1)
10 MGD	10.0	7.9	10.2
100 MGD	6.7	5.0	6.5

CCI = Sewage Treatment Plant Construction Cost Index

Source: Table 18 and Eilers, op.cit., Tables 3 and 4.

Table 20: Replacement of the Primary Clarifiers of Treatment Configuration 2 by Screens (50 mgd)

	Capital Costs, $ Million	Amortization ¢/ 1,000 Gal.	Operation & Maintenance ¢/ 1,000 Gal.	Total ¢/1,000 Gal.	Annual Cost per Household $
Sewage Alone	16.8	7.2	4.3	11.5	14.00
2.25 lb/cap/day Refuse, Primary Clarifiers	30.7	13.1	7.5	20.6	25.20
2.25 lb/cap/day Refuse, Screens	31.0	13.2	8.0	21.2	25.90

Source: Computer Simulation Model of Waste Treatment Facility

Table 21: Impact of Per Capita Refuse Generation Rates (Process Configuration 2)

Size of Plant: 500 MGD; 500,000 Inhabitants Sewered, 100 Gal/Cap/Day of Sewage

	Capital Cost, $ Million	Amortization ¢/ 1,000 Gal.	Operation and Maintenance ¢/ 1,000 Gal.	Total ¢/1,000 Gal.	Annual Cost Per Household $
Sewage Alone	16.8	7.2	4.3	11.5	14.00
2.25 lb/cap/day	30.7	13.1	7.5	20.6	25.20
3.375 lb/cap/day	37	16.1	9.3	25.4	31.00
4.5 lb/cap/day	44.5	19.1	11.2	30.3	37.00

Source: Computer Simulation Model of Waste Treatment Facility

Table 22: Cost of Sludge Handling

	Sewage Alone		Sewage + 2.25 lb/cap/day Refuse		
Plant Size, MGD	Annual Cost of Sludge Handling, $ Million	Fraction Of Total Annual Cost	Annual Cost of Sludge Handling $ Million	Fraction of Total Annual Cost	Relative Increase in Sludge Handling Costs
10	0.222	0.35	0.611	0.57	2.75
25	0.383	0.31	1.22	0.56	3.18
50	0.654	0.30	2.13	0.56	3.25
100	1.1	0.29	3.69	0.53	3.35

Source: Computer Simulation Model of Waste Treatment Facility

on Table 22. As expected, the addition of ground refuse not only increases the cost of sludge handling by a factor of about 3, but also constitutes a much larger percentage of total treatment cost, up from around 30 percent to almost 60 percent. The importance of obtaining accurate costs for sludge handling under the wet systems concept is thus clearly evident.

Notice that the relative increase in sludge handling costs increases with increasing plant size. The reason for this is the diminishing economies of scale, a phenomenon readily apparent on examination of unit costs, for example in terms of $/ton of dry sludge solids as a function of total tons of solids handled by a facility per year, as shown on Figure 36 for process configuration 2. Inspection of this Figure for a six-fold increase in sludge solids due to the addition of ground refuse at a 10 mgd facility shows a decrease in unit costs from $51/ton to about $23/ton, a decrease of $28/ton, whereas a six-fold increase at a 100 mgd facility decreases unit costs from $25/ton to $14/ton, a decrease of $11/ton.

More importantly, Figure 36 shows why costs for sludge handling at a facility treating ground refuse are so much lower than expected. And because sludge handling costs at such a facility constitute a much greater fraction of total treatment costs than if treating only sewage, it is obvious that the total cost of treatment is also much lower than might be anticipated. From Figure 36, which is derived directly from the computer model, it is clear that a 10 mgd plant treating 2.25 lb/refuse/cap/day handles as many tons of sludge solids as a 60 mgd plant treating sewage alone, and therefore it follows that the order of magnitude of sludge handling costs will be that of the conventional 60 mgd plant rather than the 10 mgd plant. In effect, therefore, the significant increase in sludge solids allows exploitation of the scale economies in sludge handling to the point where costs on a per ton of solids basis may be 50 percent less than at an equivalent plant treating sewage alone.

Notice also that the cost function for joint treatment of refuse and sewage is about $5/ton lower than the function for handling sewage solids alone. The reasons for this are explored in some detail in the separate report on sludge handling and disposal,[29] and include a sludge that is more readily dewatered, a probable elimination of conditioning chemicals, (tending to reduce the vacuum filtration costs), and higher solids concentrations to the digester (tending to reduce capital costs of digester capacity). However, it should again be stressed that these costs do not include ultimate disposal, and in particular do not include the cost of landfill disposal of grit, a cost that may be substantial depending on the haul distance. On the other hand, the costs have not been credited with possible benefits from resource recovery, especially the methane recovered from the digester which may bring as much as $9/ton of dry solids, as indicated in Equation (5) of Chapter V.

Advanced Waste Treatment. Figures 37 and 38 show two likely treatment process configurations involving advanced waste treatment technologies, and cost comparisons for 10 mgd facilities are shown on Table 23. The details of the design and cost relationships for each of the unit processes included in these treatment facilities are given in Fisette and Meier.[30]

No provision was made in these calculations for increased excess capacity or back-up facilities that would be necessary if hazardous compounds from ground refuse were indeed introduced into the waste stream. Until more information is available on such hazardous materials in refuse, it is obviously very difficult to select a process configuration to adequately handle such materials. From this viewpoint, therefore, the cost figures shown may be optimistic rather than conservative.

1988 Cost Estimates. The 1988 costs for treatment will be largely determined by the need for advanced waste treatment and to a lesser extent by the higher per capita refuse loadings. From Table 23 one may hypothesize that 1988 wet system treatment costs with advanced waste treatment will lie in the range of $40-60 per household per year; the need for advanced waste treatment alone will raise the range of annual per household costs from a typical 1973 range of $23-$35 established for the wet system concept on Table 18. For sewage alone, the increase in annual per household cost is from $12-$21 in 1973 to $30-$45 in 1988; the reason why the relative increase due to advanced waste treatment is less in the case of the wet system (about 1.7 times) than under existing concepts (about 2.5 times) is that the addition of ground refuse has little impact on the size and operation of advanced treatment processes under the assumptions outlined above.

Ultimate Disposal

The preceding cost analyses have largely avoided the problem of ultimate disposal by including an incinerator in the sludge handling scheme of all the treatment plant configurations considered. This is not to say that direct landfill might not be cheaper, but rather that incineration represents an upper bound to the costs. If the cost of sludge haul and landfill were higher than that of incineration, as might often be the case where landfill sites can only be found at some distance from the treatment facility, then clearly incineration would be chosen. In the case of treatment plants handling sewage alone one may neglect, at least in the order of magnitude calculations herein of concern, the cost of disposal of the incinerator residue and of the grit because the amounts are very small and hence the assumption of a nearby landfill site of adequate capacity appears quite tenable. But in the case of a treatment plant handling ground refuse solids, one must explicitly consider ultimate disposal in order to obtain an accurate cost comparison.

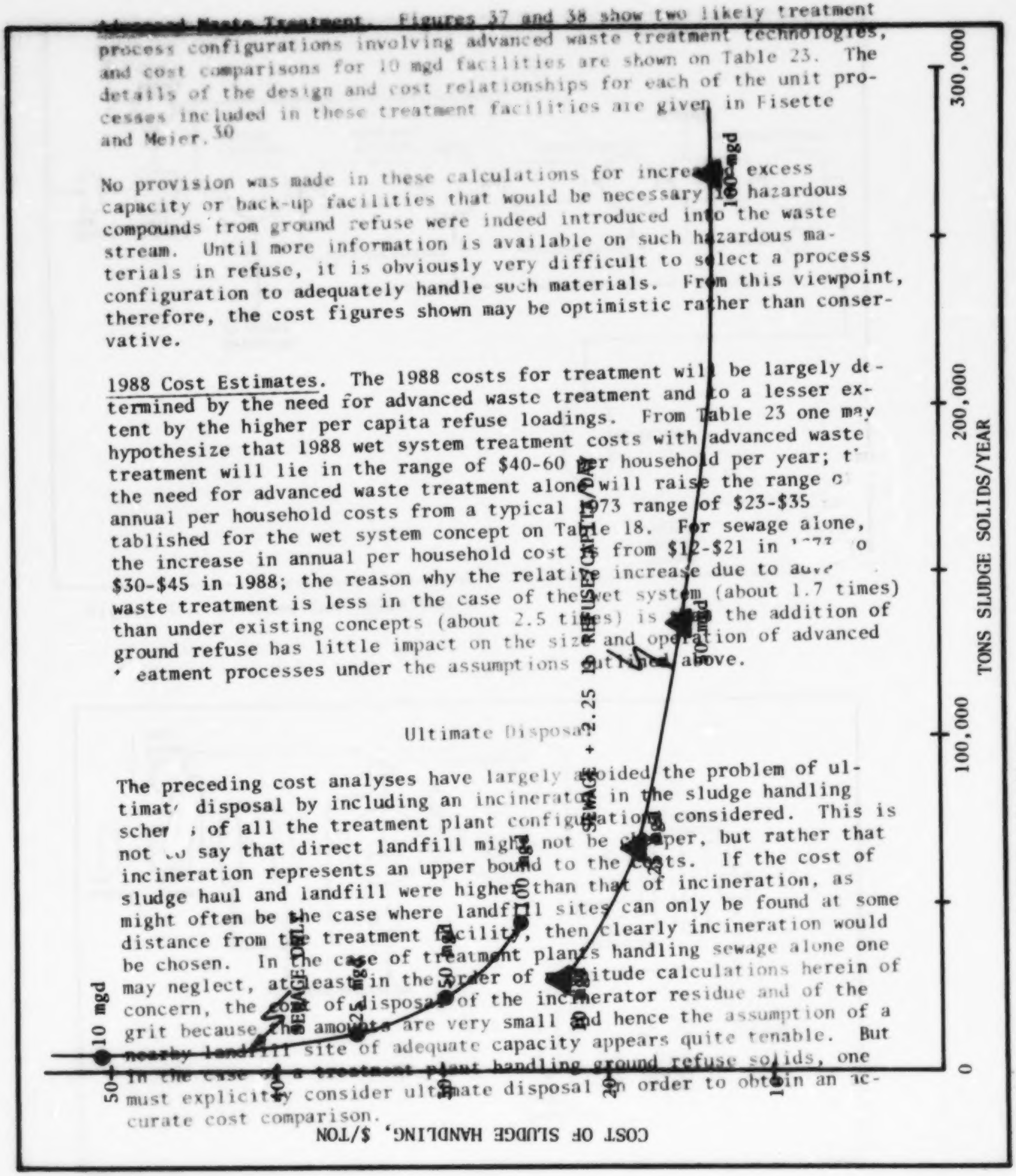

Figure 36: Cost of Sludge Handling

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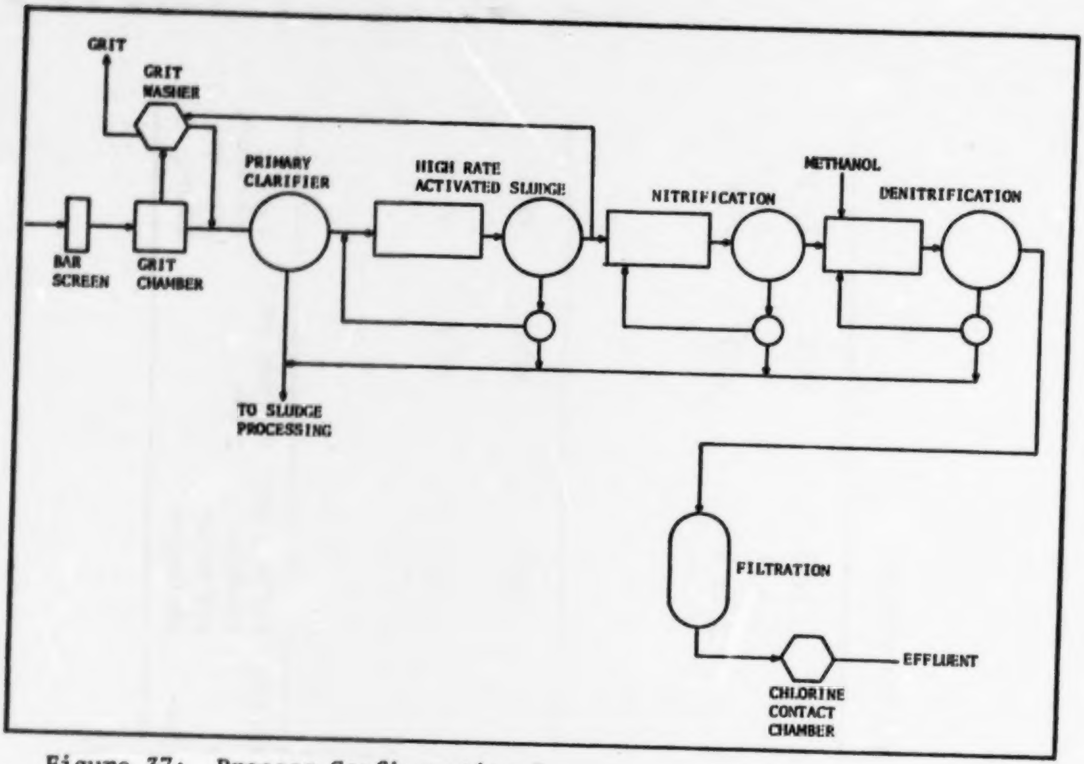
GRIT
GRIT WASHER
PRIMARY CLARIFIER
HIGH RATE ACTIVATED SLUDGE
METHANOL
NITRIFICATION
DENITRIFICATION
BAR SCREEN
GRIT CHAMBER
TO SLUDGE PROCESSING
FILTRATION
EFFLUENT
CHLORINE CONTACT CHAMBER

Figure 37: Process Configuration 3

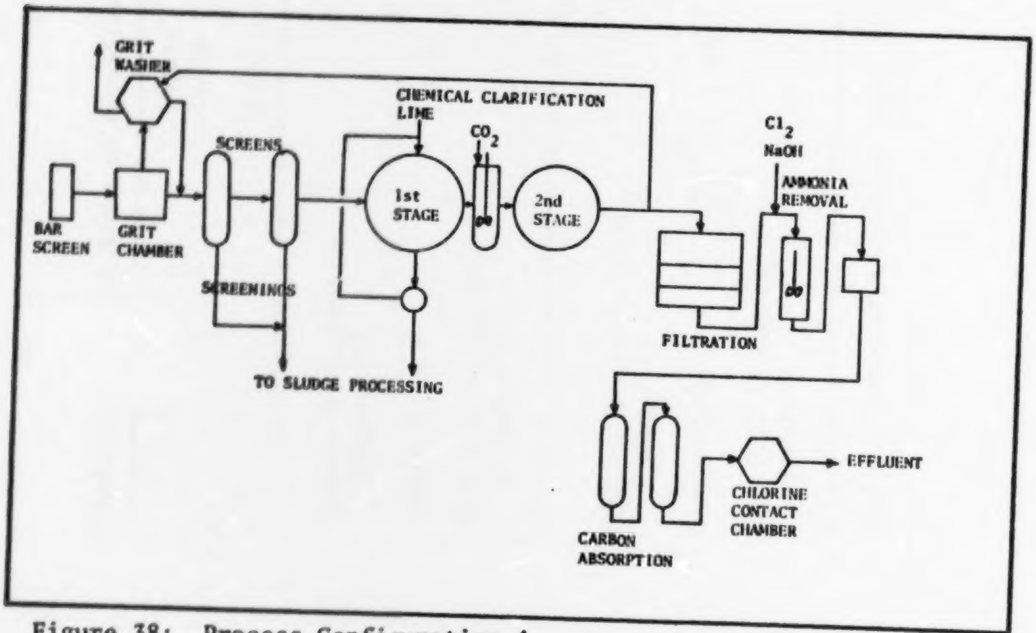
GRIT WASHER
CHEMICAL CLARIFICATION
LIME
CO_2
SCREENS
Cl_2
NaOH
AMMONIA REMOVAL
1st STAGE
2nd STAGE
BAR SCREEN
GRIT CHAMBER
SCREENINGS
FILTRATION
TO SLUDGE PROCESSING
EFFLUENT
CHLORINE CONTACT CHAMBER
CARBON ABSORPTION

Figure 38: Process Configuration 4

Table 23: Cost of Advanced Waste Treatment

	Capital Costs, $ Million	Amortization ¢/1,000 Gal.	Operation and Maintenance ¢/1,000 Gal.	Total ¢/1,000 Gal.	Annual Cost per Household $/Year
Process Configuration 3 (Figure 37)					
Sewage Alone	6.87	15.0	11.2	26.2	32.06
With 2.25 lb/cap/day of Refuse	10.16	22.1	16.1	38.2	46.7
Process Configuration 4 (Figure 38)					
Sewage Alone	6.98	14.9	19.3	34.2	41.8
With 2.25 lb/cap/day of Refuse	10.27	23.0	24.2	47.2	57.77

Source: Computer Simulation Model of Waste Treatment Facility.

In Chapter IV a calculation of the grit produced at a treatment facility handling ground refuse showed an annual production of 5.4 x 10^3 cu yds of grit, or about 4,100 tons per year. If this has to be truck-hauled only a few miles to a disposal site, the cost may be several dollars per ton. Suppose, for example, that a 20 cu yd container were used for storage and subsequent haul to a site 5 miles distant. A typical cost for truck haul might be $30 per pick-up plus $15 per hour of travel.[31] This would result in an annual haul cost of

$$\frac{5.4 \times 10^3 [\text{cu yds}]}{20 \, \frac{\text{cu yds}}{\text{pickup}}} \times 30 \, \frac{\$}{\text{pickup}} + \frac{10 \, \frac{\text{miles}}{\text{pickup}}}{25 \, \frac{\text{miles}}{\text{hour}}} \times 15 \, \frac{\$}{\text{hour}} \qquad [40]$$

$$= 9{,}720 \, \frac{\$}{\text{year}}$$

In addition, if one assumes the cost of landfill to be about $1/ton, then the total cost of grit disposal would be $9,720 + $4,100 = $13,820 per year, or about 50 cents per household.

Total System Costs

On the basis of the preceding discussions, two major factors would appear to determine the range of costs for a wet system implementation; the refuse generation rate and the size of the urban area that largely determines the degree to which scale economies can be exploited. Table 24 shows the cost ranges for each major subsystem expressed as a function of population size; where a cost range is shown as a constant over population size no economies of scale were identified in the discussion of the previous sections. A refuse generation rate of 2.25 lb/cap/day is assumed for the wet system cost estimates. It is clear from Table 24 that the range of costs of the wet system lies above the range of costs for conventional practice regardless of population size. But if the costs of the wet system grinders are excluded from the comparison, the cost ranges of wet system and conventional practice are comparable.

Cost inspection of these ranges (without grinding in the wet system case) shows that the low bounds of the ranges are comparable, whereas the high bounds of the wet system range are considerably lower. Thus under the rather restrictive assumption that the costs of grinding would be borne by the individual householder in return for convenience benefits, one may conclude that if conditions for conventional practice are unfavorable, then the wet system may offer a substantial cost saving. But if conditions for conventional practice are favorable, then the wet system offers little further advantage.

Table 24: Total System Cost Comparisons, for 1973 Conditions, in $ Per Household Per Year

Population		Collection	Disposal	Grinding	Hydraulic Transport (Sewer Maintenance for Conventional)	Treatment (Primary and Secondary and Sludgo Handling)	Haul and Disposal of Grit and Incinerator Residue	Total (Total of Wet System Excluding Grinder)
50,000	Conventional	10-40	15-43	0	7	25	0	57-115
	Wet System	2.50	2-6	80-105	8-43	39	0.5-1	132-196.5 (52-91.5)
100,000	Conventional	10-40	15-43	0	6	21	0	52-110
	Wet System	2.50	1.50-3.50	80-105	7-37	35	0.5-1	125.5-184 (46-79)
500,000	Conventional	10-40	15-43	0	4	14	0	43-101
	Wet System	1.50-2.50	1-2	80-105	5-25	25	0.5-1	113-160.5 (33-55.5)

Source: Tables 11-23 and Figures 19-26.

Table 25: Total System Comparisons for 1973 Conditions in $ Per Household Per Year (500,000 pop.)

Refuse Generation		Collection	Disposal	Grinding	Hydraulic Transport (Sewer Maintenance for Conventional)	Treatment (Primary and Secondary and Sludge Handling)	Haul and Disposal of Grit and Incinerator Residue	Total (Total of Wet System Excluding Grinder)
2.25 lb/cap/day	Conventional	10-40	15-43	0	4	14	0	43-101
	Wet System	1.50-2.50	1-2	80-105	5-25	25	0.5-1	113-160.5 (33-55.5)
3.375 lb/cap/day	Conventional	12-42	15-43	0	4	14	0	45-103
	Wet System	2-3	1.5	80-105	5-25	37	0.5-1	126-172.5 (46-67.5)
4.5 -lb/cap/day	Conventional	14-44	15-43	0	4	14	0	47-105
	Wet System	2.5-3.5	2	80-105	5-25	44.5	0.5-1	134.5-181 (54.5-76)

Source: Tables 11-23 and Figures 19-26.

The high cost of the wet system is thus largely determined by the high cost of grinding, which may constitute up to 66 percent of the total wet system cost. On the other hand, it should be noted that these engineering cost comparisons do not take into account the social costs and benefits that accrue to the wet system alternatives.

Table 25 shows total system cost comparisons for an urban area of 500,000 under increasing refuse generation rates. The cost ranges shown differ from those of Table 24 only where a dependency of cost on refuse generation rate could be clearly established. Comparison of the total system ranges with those on Table 24 shows a similar spread of costs. In fact, the largest item of variability is seen to be the cost of hydraulic transport.

Table 26 shows total system cost comparison under the assumed conditions of 1988, again as a function of population size, and expressed in 1973 dollars. Comparison with Table 24 shows the 1988 cost range for the wet system to be marginally more competitive than under present conditions. But again the cost of grinding would need to be excluded for the wet system to show real advantage.

In summary, three major conclusions can be drawn from the total system cost comparisons. Firstly, grinding constitutes the major fraction of the wet system cost, and therefore the economic feasibility of the wet system concept will be largely determined by the ability to effect substantial reductions in the unit cost of grinding. Secondly, the costs of hydraulic transport show the largest degree of variability of any wet system component, indicative of the uncertainty that still surrounds the feasibility of hydraulic transport in an existing gravity sewer system without major modifications. And finally, the expected increases in the labor costs of conventional collection are of insufficient magnitude to make the wet system concept significantly more attractive in the future. Even a 3 or 4 percent increase in labor cost (in excess of inflation) would make little difference to this conclusion. Thus it is primarily future reductions in grinding cost that would significantly improve the prospects for a wet system implementation.

Table 26: Total System Cost Comparisons for 1988 Conditions (in 1973 Dollars) as $ Per Household Per Year

Population		Collection	Disposal	Grinding	Hydraulic Transport (Sewer Maintenance for Conventional)	Treatment (Primary and Secondary and Sludge Handling)	Haul and Disposal of Grit and Incinerator Residue	Total (Total of Wet System Excluding Grinder)
50,000	Conventional	16-46	16-46	0	8	36-46	0	75-143
	Wet System	2.50-4	3.50-6	80-105	10-51	50-61	1-1.5	147-228.5 (67-123.5)
100,000	Conventional	16-46	15-43	0	7	32-42	0	70-138
	Wet System	2.50-4	2.50-4	80-105	8-43	46-57	1-1.5	140-214.5 (60-109.5)
500,000	Conventional	16-46	15-43	0	5	25-35	0	61-129
	Wet System	2.50-4	1-2	80-105	6-30	39-50	1-1.5	129.5-192.5 (49.5-87.5)

Source: Tables 11-23 and Figures 19-26.

REFERENCES

CHAPTER VI

1. This approach is typified by Partridge, L. J., and J. J. Harrington, "Quantitative Estimates for Solid Waste Management in Boston," Environmental Systems Program, Harvard University, Discussion Paper 71-4, December 1971.
2. Hirsch, W. Z., "Cost Functions of an Urban Government Service: Refuse Collection," *Review of Economics and Statistics*, 47(1), 1965, pp. 87-92, typifies this approach.
3. Data Acquisition and Analysis System, Quarterly Report, April 15, 1972.
4. Fisk, A. and A. Guzdar, "Preliminary Design of a Household Refuse Grinder," Report by Foster-Miller to EPA Solid Waste Research Laboratory, January 1973, p. 71.
5. Although the sample base covered only three months of 1972, initial analysis of the 18-month data acquired at the time of this writing indicate no significant changes.
6. Clark, R., "Measures of Efficiency in Solid Waste Collection," *J. Env. Eng. Div.*, ASCE, Vol. 99, No. EE4, p. 447-459, 1973.
7. Study of Solid Waste Disposal for the Commonwealth of Massachusetts, Report by the Raytheon Service Company, May 1972.
8. Assuming 3.5 persons per household, 3.015 x 3.5 = 10.55 lb/household/day.
9. Raytheon, *op*. *cit*., p. 2-157.
10. Santry, I. W., "Sewer Maintenance Costs," *J. WPCF*, Vol. 44, No. 7, July 1972.
11. Smith, R. and R. Eilers," Cost to the Consumer for Collection and Treatment of Wastewater," *Water Pollution Control Research Series 17090*, July 1970.
12. *Ibid*., p. 31.
13. Capital costs amortized over 50 years at 6 percent.
14. Santry, *op*. *cit*., p. 1413.
15. 31st Edition, Robert Snow Means Company, pp. 25-32, 6- and 8-inch sewers, which make up the bulk of a system, were assumed for this computation.

16. The following assumptions were used for determination of building connection costs: The pressure tubing is installed in a separate trench from a basement located pump-grinder and connected to the existing gravity sewer; the pressurized connection will consist of two-inch polyvinyl chloride (PVC) pipe, 150 feet long, rated at 160 psi. From the Dodge Construction Pricing and Scheduling Manual (1971), the cost of labor (two plumbers) and material is $1.40 and $.55 per linear foot respectively for a total of $1.95 per linear foot (=$292.50); the cost of trench excavation by tractor backhoe and backfilling in medium soil to below the frost line (say, five feet) is $1.35 for equipment and $1.00 for labor costs for a total of $2.35 per cubic yard. If the trench is two feet wide by five feet deep and 150 feet long, the total number of cubic yards is 55.6 (=$130.55); connection to basement ($25-$75); yielding a grand total of $450-$500.

17. The cost of trenching, which constitutes 30 percent of the total estimated cost, would be avoided because the pressurized line could be built at the same time and in the same trench as the other building connections (see footnote above).

18. See Chapter V, Paper Recovery.

19. Zandi, op. cit., Appendix IV. The manufacturers of such systems were very reluctant to make cost estimates in the absence of specific details of the application.

20. If 25 percent of the population were to be included, and the average life of a grinder is 15 years, then 200 million x .25/(3.5 x 15) = 0.95 million.

21. The assistance of Messrs. Smith and Eilers of the EPA Advanced Waste Treatment Research Program, Cincinnati, Ohio, is gratefully acknowledged.

22. 64K bytes of core storage is the most commonly encountered restriction at in-house computer facilities operated by consulting engineers or public works departments.

23. Meier, P., and G. R. Fisette, "Modifications to the Executive Program for Steady-State Simulation of Wastewater Treatment Facilities," Report by Curran Associates, Inc. to EPA Solid Waste Research Laboratory, Cincinnati, Ohio, March 1974.

24. Metcalf & Eddy, op. cit., p. 4-13.

25. Ibid., p. 4-12.

26. Patterson, W. L., and R. F. Bunker, "Estimating Costs and Manpower Requirements for Conventional Wastewater Treatment Facilities," Report by Black and Veatch to the Office of Research and Monitoring, EPA, October 1971, (published as Water Pollution Control Research Series 17090 DAN 10/17). The cost functions are updated to a CCI-Index of 176.1 as of January 1973.

27. Eilers, R., "Condensed One-Page Cost Estimates for Wastewater Treatment," EPA Advanced Waste Treatment Research Laboratory, Cincinnati, Ohio, November 1970.

28. The design and cost relationships used for these screens are described in Meier and Fisette, *op. cit*.

29. Kos, P., P. M. Meier and J. M. Joyce, "Economic Analysis of the Processing and Disposal of Refuse Sludges," Report by Curran Associates, Inc. to EPA Solid Waste Research Laboratory, March 1974.

30. Meier and Fisette, *op. cit*.

31. See e.g., "A Plan for Solid Waste Management in Northern Berkshire County," Report by Curran Associates, Inc., to the Berkshire County Regional Planning Commission, Pittsfield, Mass., July 1973.

CHAPTER VII

CONCLUSIONS

Technical Feasibility

Grinding. The feasibility of grinding most components of residential refuse in small, low-powered grinders has been established. Ferrous metals, heavy gauge aluminum and certain resilient, ductile items present difficulties that could only be solved by power levels not normally acceptable for household use. But the key question that surrounds grinding in the individual home is that of water requirement. If one grinds at the one percent solids concentration or less required to avoid deleterious effects in the sewers, then the result is either a significant increase in freshwater consumption (depending on the degree to which laundry effluents may be utilized) or an expensive plumbing separation to achieve domestic wastewater reuse. On the other hand, if one grinds at high consistencies, say at 6 or 7 percent, an expensive pressurized building connection is required, and there may be temporary loss of hydraulic capacity in the sewers. Consequently, there are some finely balanced trade-offs to be considered, which can only be answered in the context of a specific application.

These problems are largely avoided by grinding at neighborhood grinding facilities feeding into interceptors that are more likely to be flowing full. However, the high cost of the vacuum system required to bring the refuse from the point of generation to the point of grinding makes neighborhood grinders feasible only in the densely populated inner-city.

Hydraulic Transport in Existing Sewer Systems. Hydraulic transport of ground refuse appears to be feasible on the basis of the available evidence, but with the exception of ferrous metals. This is not a serious deficiency because household grinders will probably have insufficient power to grind them. The transport of ground aluminum and glass would appear to be feasible in appurtenances as well as straight sections of sewer provided scouring velocities of 2.5 ft/sec are present. There is thus some question as to the ability of laterals on the periphery of the sewer system to transport glass and metals, because many laterals rarely reach design flows at which the scouring velocity is present. Moreover, the concentration of refuse in sewage may reach levels that are temporarily in excess of 1.5 percent, a concentration beyond which head losses are far greater than that for water flowing alone; and consequently there may be temporary loss of hydraulic capacity that is unacceptable. Of course, if the Foster-Miller concept of grinding at 1 percent solids were always possible, this would not occur; but the evidence suggests that there may be insufficient water to accomplish this unless substantial quantities of freshwater are used in addition to whatever is stored. This question of additional water requirements, and the increase in water consumption and sewage flows, will be further analyzed in Phase II of the study.

Should modifications to the existing gravity sewers be required, the most likely solution is to modify the gravity sewer system itself to meet the slope and velocity requirements of ground refuse transport. Pressurized alternatives appear unlikely because of operational difficulties and their lack of flexibility to accommodate fluctuations in flows and solids loadings.

Treatment. The process of treating ground refuse in sewage at wastewater facilities using conventional treatment technology appears feasible. Preliminary, primary and sludge handling facilities will be the most affected by the increased solids loads, the costs of sludge handling being much higher than those encountered today, both in absolute terms and in terms of their relative contribution to total treatment costs. But if preliminary and primary facilities are properly designed and operated, the impact on conventional secondary biological treatment is likely to be marginal, the increase in BOD and suspended solids loads in secondary process influents being little greater than the load variations exhibited at existing treatment plants. There is no evidence to support the contention that the addition of ground refuse would introduce materials that are toxic to the micro-organisms on conventional biological treatment; and degradation of organic matter in the presence of ground refuse appears to take place at the same rate as if the treatment plant input were sewage alone. Moreover, there is no evidence of any significant increase in the concentration of nutrients, inorganic dissolved solids, or heavy metals.

The additional of ground refuse to sewage is not expected to have any significant impact on advanced waste treatment. Marginally higher operating costs might be expected due to the slightly higher loadings anticipated. Moreover, with the exception of potentially hazardous, nonbiodegradable compounds not removed by conventional secondary treatment, no advanced waste treatment process will be required just because of the addition of refuse. Microstrainers might be used as a tertiary polishing device at an existing facility to bring effluent quality to its former level, but for reasons of economics rather than for reasons of needing an additional treatment process.

In summary, the only potential major technical problem in treating ground refuse with conventional or advanced treatment technologies is that surrounding the possible introduction of hazardous and nonbiodegradable compounds into the environment. However, the magnitude of the problem is unknown at present, and some laboratory investigations to determine the actual presence or absence of such compounds would be indicated as a research priority of considerable importance.

Resource Recovery. Although individual local circumstances may make the recovery of glass, aluminum and paper fiber an economic proposition, the conclusion of this preliminary assessment is that the recovery of energy is the most attractive option for resource recovery under the wet systems concept. The most probable alternative in this respect is the recovery of digester gas and its use either as a substitute for natural gas or directly for the generation of peak load electric power at gas turbine-generator facilities. Market conditions are highly favorable for energy recovery and are likely to improve rather than decline in the future, regardless of the number of treatment plants practicing these options. This cannot be said for metals, glass and paper recovery, the limited markets for which would become rapidly saturated to the point of making recovery of these products uneconomic.

Economic Feasibility

The major conclusion of the preliminary economic assessment is that economic feasibility will ultimately be determined by the ability to design, manufacture and install grinders at a cost far below that anticipated for the Foster-Miller design. The expected total annual per household costs for area-wide implementation of the wet system is $114-$196, or $34-$91 exclusive of the grinder. This compares with a range for conventional practice of $43-$115. It might be argued that if the purchase and maintenance of the grinder were to be the responsibility of the individual householder, then the costs accruing to the public sector are not unfavorable, with the wet system already now justifiable on tangible costs alone in some cases. However, while it is conceivable that householders would be prepared to pay $20 per year in maintenance and an initial capital outlay of $100-$200 for reasons of convenience and aesthetics, it is unreasonable to suppose that householders will make capital outlays in the order of $500-$1,000. If indeed the responsibility for grinders were imposed on householders, then the initial capital outlay is the prime determinant of a decision to buy, not its amortized annual equivalent over its expected working life. Domestic appliances are financed over two or three years, at most, and to assume otherwise is to imply some radical innovations in the structure of the consumer credit industry.

The cost estimates for 1988 are slightly more favorable to the wet system concept, with a range of $130-$228 per household per year as compared to an anticipated conventional cost range of $67-$143. Excluding the grinder, the wet system costs would lie in the range of $50-$123. But again, the cost of the grinder appears to be the dominant cost factor.

Consequently, a major work element for Phase II will be a study of trends in the domestic appliance industry, focused in particular on the historical cost trends in the domestic appliance industry, focused in particular on the historical cost trends of other domestic appliances such as washing machines, garbage grinders and dishwashers which resemble the refuse grinder both in size and electro-mechanical sophistication. The economies of scale of mass production are substantial, and must therefore be examined very carefully in order that an accurate picture of future costs can be made.

The foregoing cost comparisons have not considered the social benefits of the wet system concept, and are therefore biased in favor of existing practice. Phase II will attempt to quantify these social benefits and to make comparisons based on total social costs rather than on engineered costs alone. Pending the outcome of this assessment, it is nevertheless clear that the cost of household grinding is the most important determinant of total system cost.

Recommendations for Further Research

The recommendations for further research that follow from the foregoing analyses fall into four major categories:

1. Priorities for the detailed systems analyses to be conducted in Phase II as a continuation of the work described in this report;
2. Treatability studies;
3. Dynamic simulations of hydraulic studies in sewers; and
4. Other research dependent on the successful completion of the three preceding items. These are of lesser urgency, but nevertheless of some consequence to more definitive conclusions as to the overall economic and technical feasibility of the concept.

Priorities for Phase II. The preliminary economic assessment points to two areas of urgency in the forthcoming detailed systems analysis of Phase II. The first calls for a much more refined analysis of grinding costs and the institutional arrangements necessary for grinder purchase and maintenance. The results of this analysis will largely determine the economic feasibility of the wet systems concept using the existing grinding design proposed by Foster-Miller. If the refined analysis shows the existing grinding concept to carry the excessive economic penalties indicated in the preliminary assessment, then recommendations for further development work in the grinding area will be formulated.

The second area of especial urgency concerns the optimization of sludge handling and disposal alternatives at the treatment plant. Although laboratory data on the characteristics of the sewage solids-refuse sludge is needed for a final determination of costs, the necessity for a systematic evaluation of the trade-offs between individual unit operations of sludge handling and disposal is clearly indicated. The very changed conditions encountered when ground refuse constitutes the major portion of the sludge results in radically changed operating conditions and interrelationships for most sludge handling processes. Also, conventional design relationships and orders of magnitude of costs appear to be very different.

Treatability Studies. It is recommended that further studies be conducted on the physical and chemical composition of ground refuse in sewage, and on the amenability to biological treatment. In addition to the tests run by Metcalf & Eddy (as described in Chapter IV), the studies should include bench scale biological treatability studies, determination of sludge characteristics, and analyses for a selection of specific potentially hazardous compounds such as pesticides. In order to gain information on the design of preliminary and primary treatment processes, tests should also be run on typical treatment plant influents, and not only on supernatants from primary settling as in the Metcalf & Eddy study. For the analyses to be statistically significant, and thus to represent an adequate basis for generalizations, a substantial number of samples from different parts of the country should be analyzed, each set of analyses on the ground refuse-sewage mixture to be run against a sewage sample without the ground refuse. The program of tests should be formulated with the assistance of a statistician competent in the field of the statistical design of experiments. The objective of these studies would be to confirm or negate the tentative but generally favorable conclusions with respect to treatability reached in this report, conclusions that can well be questioned because they are based on the single sample analyzed by Metcalf & Eddy. Such further detailed laboratory studies are clearly required before any demonstration, even at a very small scale, can be undertaken at a real sewage treatment plant.

Specific recommendations for the treatability studies, in addition to the experiments run by Metcalf & Eddy, include:

1. Ground refuse concentrations should be in the range of 0.3 to 1.2 percent by weight (on a dry solids basis).

2. Determination of particle size distribution of a simulated treatment plant inflow that underlies design of screening processes.

3. Determination of grease and oil in the simulated treatment plant inflow.

4. Settling tests to determine settling characteristics that underlie design of primary sedimentation facilities, and quantitative determination of floatables.

5. Bench scale biological treatability studies on supernatant of primary settling to simulate activated sludge process, if possible on a continuous rather than batch process basis. It is important to measure total organic carbon, nutrient and metal ion concentrations of secondary effluent in addition to standard BOD and SS determinations.

6. Determination of heavy metal ion concentrations, including mercury, copper, chromium, iron, zinc, lead, cadmium, nickel and aluminum of grinder effluent, treatment plant inflow, primary sludge and the primary settling supernatant.

7. Determination of quantitative sludge characteristics such as specific resistance, viscosity and coefficient of compressibility, so that dewatering processes may be satisfactorily modelled. Test sludges should be obtained from both screens and simulated settling basins, and should be free of grit (as a grit removal would be a mandatory initial preliminary treatment step).

8. Gas chromatograph or other advanced instrumentation methods to determine the presence, and, if possible, the concentration of specific hazardous and nonbiodegradable materials in the effluent of the simulated secondary treatment effluent.

Dynamic Simulation of Hydraulic Transport in Sewers. As noted in Chapter III, the generally favorable conclusions on the feasibility of transport in gravity sewer systems are based on experiments run under controlled laboratory conditions. However, the effect of time-dependent fluctuations in loads and hydraulic conditions are unexplored; yet as elaborated in Chapter III, extreme conditions, however temporary, could cause serious problems, especially in the laterals at the periphery of the sewer system. Consequently, there is a need for dynamic simulations of the conditions resulting from the injection of ground refuse into small diameter sewers typical of residential areas. At a very minimum, these should be made with a test length of 6-inch sewer several hundred feet in length, and include several building connections at which sewage and ground refuse is introduced, and a range of typical appurtenances. It is important that probable variations in flow and solids concentrations should be simulated overy cycles in excess of 24 hours so that long term effects and the occurrence of temporary but serious problems can be satisfactorily determined. It is also recommended that fresh refuse be used and ground at the site of the experiments rather than using dried hydropulped refuse as a source as in some of the Foster-Miller experiments. While this may cause additional expense and possibly odor problems to those performing the experiments, it is important that the simulation reflects real conditions as closely as possible if the uncertainties are to be clarified.

Other Recommended Research. Given that further detailed treatability studies show no potential problems with respect to hazardous or non-biodegradable materials, some demonstration tests in real sewers are recommended. These tests should be conducted in old sewers where blockages even under existing practice are known to be frequent, because realistic laboratory simulations of the older sewers plagued by faulty joints, root intrusions, encrustations and other problems causing frequent blockages actually encountered in so many urban areas are obviously almost impossible to achieve. Yet in many central urban areas the need for excessive maintenance of existing sewers might well completely invalidate hydraulic transport in existing sewer systems.

Given further the completion of the treatability study and the dynamic simulation of hydraulic transport, an update of the cost analyses presented in this report would be indicated. The new information will

allow much greater precision to the cost estimates developed by this preliminary assessment and the Phase II studies, and the computer models prepared by these studies will allow efficient and rapid updating. This update is regarded as essential before a commitment is made to invest research monies into any field demonstration project of the entire system.

APPENDIX A: LIST OF ABBREVIATIONS

BOD	Biochemical Oxygen Demand
Btu	British Thermal Unit
COD	Chemical Oxygen Demand
cu ft	Cubic feet
cu ft/Mg	Cubic feet per million gallons
cu yd	Cubic yard
fps	Feet per second
gal/cap/day	Gallons per capita per day
Hg	Mercury
HH	Household
HP	Horsepower
Kw	Kilowatt
Kwh	Kilowatt-hour
lb/cap/day	Pounds per capita per day
LNG	Liquified Natural Gas
Mg	Million gallons
Mgd	Million gallons per day
Mg/l	Milligrams per liter
µg/l	Milligrams per liter
mm	Millimeters
MW	Megawatt
N	Nitrogen
P	Phosphorus
ppb	Parts per billion
ppm	Parts per million
SMSA	Standard Metropolitan Statistical Area
SS	Suspended solids
TKN	Total Kjehdahl Nitrogen
VS	Volatile solids

APPENDIX B: METRIC EQUIVALENTS

American Unit	x	Multiplier	=	Metric Unit
yards		0.9144		meters, m
feet		0.3048		meters, m
inches		2.54		centimeter, cm
cu ft		28.316		litres, l
gallon		3.7854		litres, l
cu yd		0.76		cubic meters, m^3
lb		0.45359		kilogram, kg
ton		907.184		kilogram, kg
Mgd		0.0438		cubic meters/sec
cu ft/sec		0.0283		cubic meters/sec
ft/sec		0.305		meters/sec